This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.

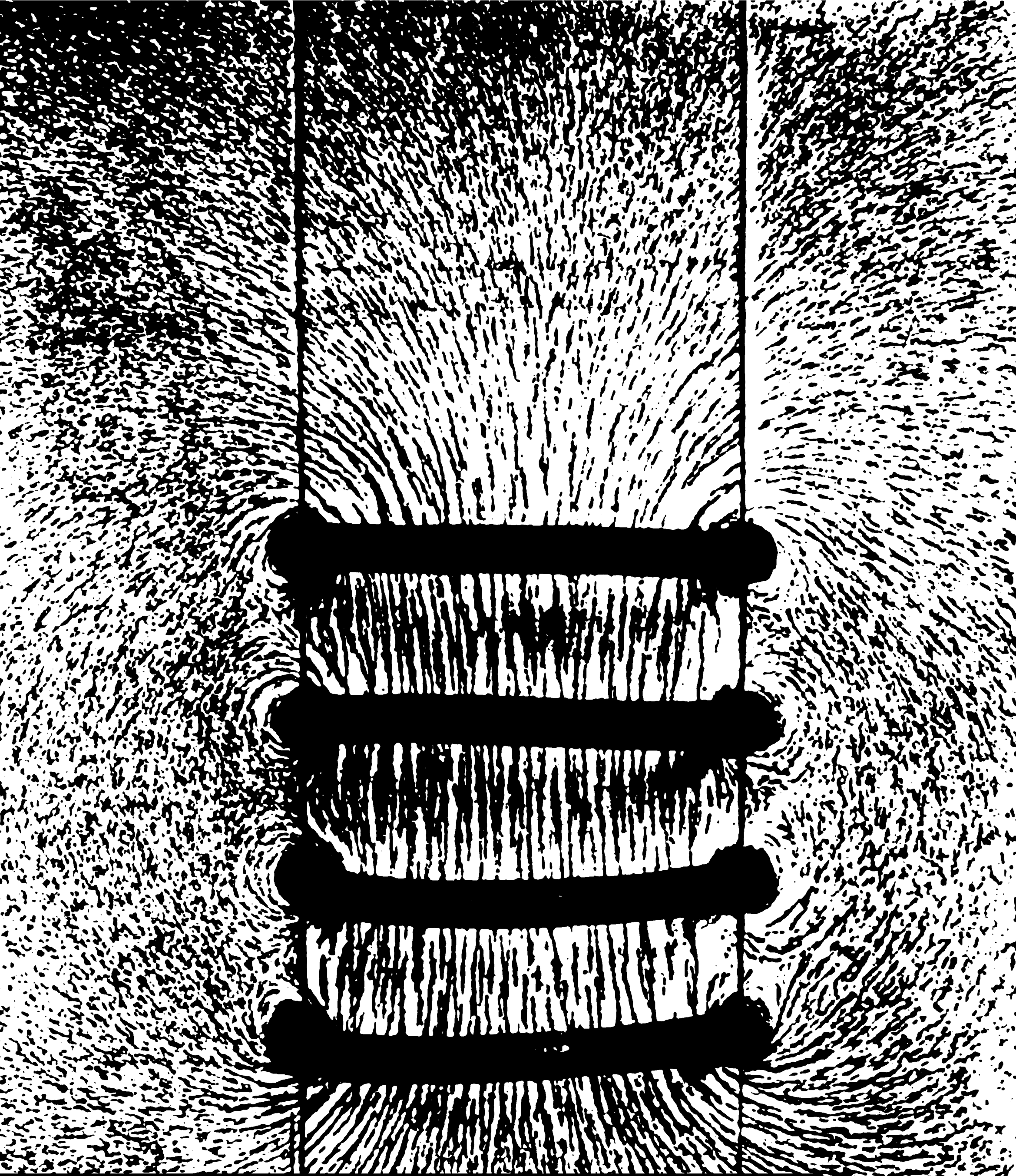
+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.

+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.

+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

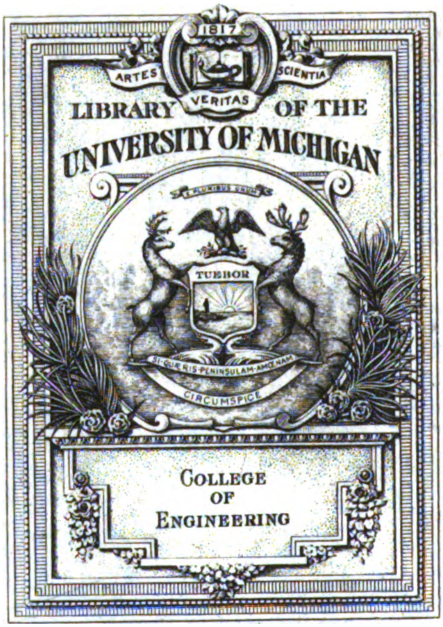
About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`



Outlines of electrical engineering

Harold H. Simmons


1817
ARTES VERITAS SCIENTIA
LIBRARY OF THE
UNIVERSITY OF MICHIGAN
TUEBOR
SI QUAERIS PENINSULAM AMOENAM
CIRCUMSPICE
COLLEGE
OF
ENGINEERING

Engin. Library
TK
145
.S59

OUTLINES OF
ELECTRICAL ENGINEERING

OUTLINES OF
ELECTRICAL ENGINEERING

BY

HAROLD H. SIMMONS, A.M.I.E.E.

LECTURER IN ELECTRICAL ENGINEERING AT FINSBURY TECHNICAL COLLEGE; FORMERLY HEAD OF THE ELECTRICAL ENGINEERING DEPARTMENT OF THE GOLDSMITHS' INSTITUTE

ILLUSTRATED

CASSELL AND COMPANY, LIMITED
LONDON, PARIS, NEW YORK, TORONTO AND MELBOUR
MCMVIII

ALL RIGHTS RESERVED

PREFACE

THE main object of this work is to present a general survey of the principles and operations of electrical engineering. The treatment of each subject in so wide a range is necessarily brief, but it is hoped that the endeavour to present in each case a clear and precise, although general, impression has been successful.

In the case of those subjects on which very numerous excellent treatises are available—such, for example, as telegraphy—the aim in the present work has been rather to fill gaps which appear to exist in the current literature. The rapid development of electro-chemistry has prohibited any detailed reference to its more recent commercial applications, electro-deposition alone being dealt with in detail.

The author wishes to express his indebtedness and thanks to the manufacturing firms whose names appear in the text for information respecting their products, and for the use of illustrations and drawings.

The chapters on wireless telegraphy are due to Mr. R. P. Howgrave-Graham, and those on dynamo design to Messrs. F. I. Hiss and A. C. Lock. The author also wishes gratefully to acknowledge the invaluable and untiring help of his assistants, Messrs. Charles E. Abell and J. Arthur Cook.

Permission to reproduce illustrations has been kindly given by the Council of the Institution of Electrical Engineers and by the proprietors of *The Electrical Engineer.* Should any of the other numerous sources which have been drawn upon for illustrations have escaped acknowledgment in the text, the author begs to tender an apology and asks to be informed of the omission.

H. H. S.

CONTENTS

PAGE
INTRODUCTION 1

SECTION I.—CIRCUITS AND CONDUCTORS.

CHAPTER
I. The Electric Circuit 4
II. Conductors 12
III. Simple and Complex Circuits 21

SECTION II.—PRIMARY AND SECONDARY CELLS.

I. The Voltaic Cell 35
II. Types of Cells 50
III. Accumulators 64

SECTION III.—ELECTRO-DEPOSITION OF METALS.

I. Introductory . . . .
II. Electroplating . . . .
III. Plating with Silver and Nickel 1
IV. Equipment and Management of Plating Shop . . . 1
V. Electrotyping 1

SECTION IV.—THE MAGNETIC CIRCUIT AND INDUCTION.

I. General Magnetic Effects 16
II. Magnetic Flux and Field 17
III. The Magnetic Circuit 192
IV. Magneto-Electric Induction 227

SECTION V.—INSTRUMENTS AND TESTING.

I. Units 235
II. Galvanometers 244
III. Continuous Current Commercial Measuring Instruments . 259
IV. Alternating Current Measurements and Measuring Instruments 283
V. Methods of Testing 302

SECTION VI.—ALTERNATING CURRENTS.

I. Properties of Unsteady Currents 348
II. Alternating Current Circuits 367
III. Calculation of Alternating Values 385
IV. Polyphase 394
V. Alternating Current Transformers 404

SECTION VII.—DYNAMOS AND MOTORS.

CHAPTER PAGE
I. ELEMENTARY CONSIDERATIONS 416
II. THE DESIGN OF CONTINUOUS CURRENT MACHINERY . . . 427
III. DESCRIPTION AND PERFORMANCE OF CONTINUOUS CURRENT DYNAMOS AND MOTORS 458
IV. ALTERNATING CURRENT MACHINES 508
V. ALTERNATORS AND TRANSFORMERS 516
VI. INDUCTION MOTORS 570
VII. MOTOR GENERATORS AND ROTARY CONVERTERS 620
VIII. MOTOR PRINCIPLES AND DESIGN TESTING 632
IX. WORKS TESTING 659

SECTION VIII.—LIGHTING AND METERS.

I. LAMPS 684
II. INTERIOR WIRING 705
III. METERS 721

SECTION IX.—SWITCHGEAR.

I. SWITCHES AND SWITCHBOARD 734
II. BOOSTERS, BALANCERS AND SPECIAL SWITCHGEAR 749

SECTION X.—TRANSMISSION AND DISTRIBUTION.

I. SYSTEMS OF DISTRIBUTION 762
II. UNDERGROUND CABLES 773
III. TRANSMISSION 780

SECTION XI.—ELECTRIC TRACTION.

I. EQUIPMENT OF TRAMWAY CARS AND TRACK 787
II. TRAMWAY SYSTEMS: THE OVERHEAD SYSTEM 801
III. CONDUIT AND SURFACE CONTACT SYSTEMS 807
IV. RAILWAYS 815

SECTION XII.—TELEGRAPHY.

I. GENERAL PRINCIPLES 829
II. ELECTRIC OSCILLATIONS 839
III. ELECTRIC WAVES 846
IV. WIRELESS TELEGRAPHY 851

SECTION XIII.—TELEPHONY.

I. TRANSMITTERS, RECEIVERS AND AUXILIARY APPARATUS 875
II. TELEPHONE SYSTEMS AND SWITCHGEAR 886
III. LINE CONSTRUCTION 910

LIST OF PLATES

PLATE *To face p.*

I. Section of Commutator for 500 K.W. Motor Generator by Electric Construction Company 432

II. Sections of 105 K.W. 400 R.P.M. 6-pole Compound Generator by Laurence Scott & Co., giving 1,000 amps. at 100–105 volts 468

III. 600 K.W. 300 R.P.M. 500 volt 8-pole Compound Generator by the Lancashire Dynamo and Motor Company 474

IV. Carcase and Pole Construction of Johnson and Phillips 50 H.P. 950 R.P.M. 4-pole Motor 490

V. Half-Sectional View of Two Types of Armature for Field System shown in Plate IV. Commutator for 220 volts shown in Section, that for 440 volts in Elevation 490

VI. 20 H.P. 220 volt Variable Speed Motor by Laurence Scott and Co. Speeds from 250 to 1,000 R.P.M. 492

VII. Details of Continuous-current 40 H.P. 6-pole 400 volt Enclosed Variable Speed Motor by Laurence Scott and Co., showing Shunt and Series Field Coils Speed Variation, 0–400 R.P.M. 496

VIII. 3,000 K.W. 6,600 volt 25 ∿ 95 R.P.M. Three-phase Alternator by Electric Construction Company in London County Council Station at Greenwich . 540

IX. 440 K.V.A. 1,110 volt 50 ∿ 97 R.P.M. Three-phase Alternator with 62 poles, by Johnson and Phillips, Limited 542

X. Detail Drawings of 3,000 kilowatt 6,700 volt 25 ∿ 750 R.P.M. Three-phase Dick, Kerr Turbo-alternator at Glasgow, showing Field and Armature Constructions 548

XI. Sectional Views of 75 H.P. 50 ∿ 480 R.P.M. Three-phase Induction Motor, with External Enclosed Slip Rings (Lancashire Dynamo and Motor Company) 600

XII. Details of 90 K.V.A., 200 volt, 750 R.P.M. Single-phase Induction Motor by Johnson and Phillips 612

XIII. Continuous-current to Three-phase Motor Generator by Johnson and Phillips. The Continuous-current Motor of 30 H.P. at 460 volts. Generator of Revolving Field Type, 20 K.V.A., 200 volts, 50 ∿. Speed, 1,000 R.P.M. . . 624

XIV. Single-phase to Continuous-current Motor Generator by Johnson and Phillips. Alternating-current Motor, 90 K.V.A., 200 volts; Direct-current Generator, 66 K.W., 200 volts. Speed 770 to 750 R.P.M. 626

OUTLINES OF ELECTRICAL ENGINEERING

INTRODUCTION

ONE of the most common of the errors into which the student of applied science is liable to fall is the thought that when names have been given to observed physical phenomena, and when their sequence and interdependence are fairly well understood, there is no need of further elucidation or investigation of the phenomena themselves; that they are, in a word, perfectly understood. The error is great, and the danger of falling into it is greater for those whose attention is chiefly confined to applied science than for those who are occupied with pure science and abstract theory. It is essential for the latter class, and for the former it cannot be unimportant, to have some conception of what may be termed the mechanism of the phenomena in question. Such a conception, if accurately based, may obviously lead to progress in the application of the phenomena to engineering and other problems, and it is unquestionably useful. It will not, therefore, be out of place, in such a work as the present one, to make reference at the outset to some of the theories of electricity which have been and are in vogue, and to emphasise the greatness of our ignorance and the instability of our abstract theories as much as the great range of our real knowledge. In order to do this, it is necessary in the first place to have in review, in the briefest manner possible, a few of the more prominent facts with which the earlier investigators of electrical science were familiar.

The very earliest electrical phenomena to be known and studied were those of electrification by friction. The fact that amber when rubbed possessed a peculiar property of attracting small objects had been known for many centuries previously, and a Dr. Gilbert, in Queen Elizabeth's time, finding other substances to behave similarly, described them as "electrics" (Greek, *elektron* = amber). This behaviour was for a long time the only recognised evidence of an electrified state. It was later found that, for example, two pieces of glass rubbed with silk repelled one another, while a piece of glass and a piece of sulphur each rubbed with silk attracted one another.*

At a time when heat was regarded as a fluid which could be squeezed out of a piece of iron, by hammering it on an anvil, and so making it hot, it is not surprising that electrical phenomena should have been attributed to fluids, even though such fluids had to be conceived as occupying an inappreciable space and having no weight. To account for the attraction of oppositely electrified bodies, like the glass and sulphur above referred to, and the repulsion of similarly electrified bodies, two opposite fluids were conceived, the one termed vitreous, the other resinous, terms which were subsequently and by common consent abandoned in favour of "positive" and "negative" respectively. The repulsion and attraction were regarded as taking place between the fluids, and as being transmitted from them to the bodies on which they were found.

---

* It is not asserted that the materials mentioned were experimented with precisely in this way; further, in any attempt to repeat these results, it must be borne in mind that different specimens of the same material will sometimes exhibit opposite results when rubbed with the same substance.

Following this came the discoveries of Galvani and Volta, which, however, were not for some time recognised as being of an electrical nature. These discoveries included the famous experiments of Galvani upon the frog's leg and Volta's work on the voltaic cell and pile. Briefly described, these may be said to have been the discovery, on the one hand, of electrification by the contact of dissimilar materials as distinct from friction between them, and, on the other, of a means (the voltaic cell) of providing a continuously acting source of electrification which could be applied to bodies which were being continuously robbed of the "electrical fluids" with which they were supplied by the cell. Very much more recently, electrification by rubbing has come to be regarded as due to the intimate contact of dissimilar bodies over a large surface which is produced by the motion and pressure of the rubbing. Selecting only one discovery as being necessary to our present treatment of the subject, we will briefly describe the action of the voltaic cell, in the light of the then accepted two-fluid theory. If a strip of each of two metals be dipped into an acid solution without touching one another either inside or outside the solution—say, for example, a piece of copper and a piece of zinc in a solution of sulphuric acid—the part of the copper outside the liquid can be shown to be charged with "positive electricity," and the zinc outside the liquid with "negative electricity." No difference could be detected, nor can be detected, between the electrification of the copper and the zinc rods and the electrification of the glass and sulphur already referred to, except indeed in degree. These charges could be made to "neutralise" one another by making the zinc and copper touch each other, but electrification was again evident when they were parted.

These facts brought about the necessity of conceiving a continuous flow from copper to zinc, and from zinc to copper, of mutually neutralising quantities of the positive and negative fluids respectively. Since this double flow could be effected through a wire joining the copper to the zinc quite as well as by allowing the zinc and copper to touch outside the liquid, it became necessary to conceive the simultaneous flow in the wire of two currents of a fluid, *i.e.* of "electricity," in opposite directions, and the difficulty of this conception caused the two-fluid theory ultimately to give way to a single-fluid theory. According to this the former "positive charge," or "positive electrification," was regarded as a surplus above, and a "negative electrification" as a deficit below, a supposed normal quantity of the one fluid which all bodies are to be regarded as possessing. In this way the voltaic cell came to be regarded as analogous to a pump serving to pump the electrical fluid out through the copper and along the wire back to the zinc, through the cell out at the copper again, and so on continuously, like water through a pipe. The analogy between water and the single fluid is so complete in this respect as to be very useful. Water is universally distributed throughout nature to such an extent that no substance or object, in its natural condition, can be said to be chemically free of water. Further, we have large quantities of water in lakes, rivers, &c., and, above all, in the sea. Water cannot be created, but its distribution, its normal or natural distribution, may be easily disturbed. If it be disturbed, there is a tendency to return to the normal condition. The disturbance may be effected by a pump belonging to a waterworks, which draws water from a low level and distributes it to cisterns in houses, whence it tends to gravitate to its old level. Or the disturbance may be effected by a fire, used to drive the water from a wet cloth into the air : here again, the dry cloth tends, as we say, to take up moisture from the air, but we might as well say the water tends to return to the cloth. In all these points the single-fluid theory of electricity puts it on a perfect parallel with water in nature. So long has this theory held its ground, and, moreover, during a period of such tremendous growth of electrical knowledge, that almost, if not quite, all the terms in present use in electro-technics both bear the impress of the single-fluid theory and can only be properly employed in the light of it. It is precisely because this theory has held sway during a period of such development that the terminology is so expressive and so suggestive of the sequence of phenomena, and is consequently so easy and convenient in use. This terminology will therefore die hard if it die at all, and at the present time it has continually to be used by a scientist in reference to phenomena to support a new theory with which the terms are sometimes glaringly at variance. The stages of progress from the time of the single-fluid theory to the present day cannot be dealt with at all fully in a work of this scope, and indeed at this point must only be referred to with the utmost brevity.

A most important step was the recognition of the electro - magnetic nature of light, and another that of the fact that the *energy* transmitted by "an electric current" is in reality transmitted not through the wire which is said to "carry the current," but through all the space surrounding that wire, entering the wire through its surface and appearing partly as an "electric current," partly as heat, or as some other form of energy. At present the most recent developments affecting the accepted theory have been in the domain of electro-chemistry and molecular physics, and these developments bid fair to overturn the long-accepted atomic theories of chemistry and to impose upon chemists the necessity of looking at their huge array of chemical reactions in an entirely new light. It is very comforting to all concerned, authors and readers alike, at a juncture like this, to bear in mind that well established "facts," that is to say sequence of phenomena, which have been and can be obtained again and again with certainty, remain unchanged, and that all one has to do is to modify that conception of the mechanism of the phenomena to which reference was made at the beginning of these remarks. Very briefly stated, the electro-magnetic theory of light may be said to have entailed a conception of waves or undulations in the ether in the place of a flow of a material fluid "electricity"; while the recent developments just mentioned force the physicist (if not the chemist at present) to regard the atom as being in all cases a combination of two parts, one of which is electrical, and may or may not be material also, and the other material. The highly electrical part is called an "electron," and the other is probably the atom proper, the combination of the two being called an "ion."

The object of this introduction will have been attained if it cause the reader of the following pages to bear constantly in mind that the terminology employed, although enabling him to follow, and to a large extent to predict, the sequence of phenomena, is hardly compatible with the most modern theory. The terminology employed is extremely useful ; and, after all, terms are only terms, and not facts.

SECTION I.

CIRCUITS AND CONDUCTORS.

CHAPTER I.—THE ELECTRIC CIRCUIT.

E.M.F., CURRENT, AND RESISTANCE—THE EFFECTS OF A CURRENT—WORK, ENERGY, AND POWER—CONDENSERS.

THE single-fluid theory of electricity, as has already been pointed out, regards the voltaic cell pretty much in the light of a pump, and its action as the maintenance of a current of electricity in flow through a circuit. In the case described the circuit consists of the copper rod, the wire, the zinc, and the sulphuric acid, through all of which portions in succession the current continuously flows so long as the cell is at work. In the light of that theory it may well be asked why the current should confine itself to that circuit, and not wander out in all directions from, say, the copper, and return by any and every imaginable path it might happen to choose. The answer and the reason are not far to seek. If any portion of the circuit above referred to be replaced by an object of exactly similar shape and size to the one removed, but of different material, the strength of the current will at once be affected. If, for example, the wire described were a copper one, and it were to be replaced by an iron one, the flow would be reduced; if by a silver one, it would be increased; if by a rod of glass of the same shape and size, it would be stopped. We should find a large number of substances behave in the same way as glass; and, in short, nearly all materials could be put into one or the other of two categories, the one containing materials which permit a current to flow along them, and the other materials which do not, or which, if they do at all, do so to such an infinitesimal degree as to make the current quite unobservable. The first category, then, contains conductors, and the second non-conductors of electricity. Properly speaking, it is only a question of degree, for the best conductors offer some opposition, and the worst non-conductors afford some passage. To these two categories a third may be added in preference to dividing the former into two, this third category containing substances which are known as electrolytes, to which more detailed reference will be made later.

The following lists include the most important substances classed under the headings of Conductors, Electrolytes and Non-conductors (or Insulators).

CONDUCTORS.	ELECTROLYTES.	INSULATORS.
All the metals. Carbon.	Solutions of acids. Solutions of salts. Fused salts. Water.	Dry air. Porcelain. Glass. Mica. Gums. Oils, fats, and waxes. Indiarubber. Guttapercha. Pure water. Silk. Furs & wools. Cotton. Wood.

To the list of insulators must be added a continually increasing number of artificial preparations, mostly of great value.

Reverting now to the voltaic circuit, we see that the current, on reaching the copper at the top of the liquid, finds itself in a metal surrounded by a non-conductor, the air. Its path is thus restricted to the metal, along which it must therefore proceed until, reaching the zinc, still surrounded by air, it passes below the surface of the liquid. Here it is in contact with an electrolyte, into which it at once spreads in all directions, finding itself, however, hemmed in on each side and underneath by the non-conducting glass vessel, and on top by the air. Having traversed the electrolyte, it enters the wetted surface of the copper at every point, and so passes away again to the external circuit, as that portion which is external to the cell is called.

It must be obvious that if, as was above stated, the best conductors offer some opposition to the passage of a current, some force must be imagined, when a current is flowing, as overcoming this opposition and maintaining the current. This force is called an electro-motive force, or the electro-motive force of the circuit, and a current cannot flow in any circuit unless there be an electro-motive force at work to produce it, that is to maintain it. Now, if a force overcomes any kind of opposition whatever, work is of necessity done; this is very clearly seen in the case of a lifting force overcoming the opposition of gravity, that is overcoming what is called the weight of the object.

In the case of a lifted mass, the work that has been done can be recovered by allowing the object to descend again to the point from which it was lifted, and the work may be said, therefore, to be stored in the body while it is in its lifted position. If, on the other hand, we see a force overcoming the opposition known as friction, as when a heavy body is pushed over a rough surface, there is not an obvious storage of the work; work is, however, indestructible, and the question at once arises "What has become of it?" Actually the work done in overcoming the friction has taken another shape, and, although it may not be very apparent in many cases, it has been transformed into heat. Now, there are such things as heat engines, and could the whole of that heat produced by the friction be collected and utilised in an engine which wasted none, that engine could be made to push the weight back to its original position against the same forces of friction acting in the opposite direction. The work done in overcoming the friction may therefore be considered to have been stored up in the heat produced, and, indeed, a large portion of it could be so stored up for a very considerable time. In our electric circuit we find a very similar state of affairs. The electro-motive force maintaining the current overcomes the opposition of the conductor, and work is therefore done, but such work is transformed at once into heat, and is therefore only recoverable by collecting, storing, and utilising that heat. An E.M.F. (the commonly accepted abbreviation for electro-motive force) may, however, be utilised in a circuit in some other way than in overcoming resistance (as the opposition of the conductor is called); and such a case is analogous to that of the lifting of a weight. The force lifting the weight had to overcome an opposing force, and no transformation into heat occurred. So in the analogous electrical case, an E.M.F. may do work in overcoming an opposing E.M.F., and in all such cases the work done is theoretically recoverable, though it is not always so in practice. In no case, of course, is the work, or, as it is sometimes called, the energy, destroyed; it is always either stored up in a recoverable form or dissipated in such a way as to be non-collectable for recovery, or in a non-usable form if collected. This may sound paradoxical, but is at once clear when it is considered that the heat form of the energy dissipated by the resistance of a conductor is recoverable in the sense that it may be used in the heat engine, but it may from the disposition of the circuit be non-collectable, and thus escape to surrounding objects. On the other hand, the energy may be utilised in overcoming an

E.M.F. to effect some chemical operation which is not reversible, the energy being in this case stored in the mutual relationship of the resulting products, which cannot be made to re-combine directly with one another. The energy, though collected, is thus not recoverable in the same form, and perhaps not usefully recoverable at all, except in that possibly at the end of a series of troublesome chemical operations involving the said products less heat will have been necessary than if the electrical energy had not been expended in preparing them.

E.M.F., CURRENT, AND RESISTANCE.

We now find ourselves by a natural and logical process dealing with four ideas in connection with the electric circuit, viz. the so-called current, resistance and electro-motive force, and work. These have to be simultaneously considered because they are simultaneously in evidence. The first three are the fundamental properties ot an electric circuit, and all other known properties of the circuit can be reduced to terms of one or another ot these.

It is worth while remarking here that our ideas have taken somewhat definite form only because we have tacitly accepted the single-fluid theory.

THE EFFECTS OF A CURRENT.

Referring once more to our simple circuit containing a voltaic cell, the following effects may all be observed when the circuit is completed : (*a*) the zinc is gradually eaten away ; (*b*) bubbles of gases are formed on the copper and zinc rods ; (*c*) the acid is gradually changed (in the present case into zinc sulphate) ; (*d*) the copper wire forming the external circuit is warmed ; (*e*) a compass needle placed near the copper wire is deflected. We sum up all these effects in a single phrase by saying that "an electric current is flowing through the circuit."

A further fact might have been noted if we had cut the copper wire and inserted in the gap thus formed in the circuit a device known as an electrolytic bath. Such a device may consist of a glass vessel containing a solution of, say, copper sulphate into which two copper plates dip without touching one another. The plates are called *electrodes*, and the one by which the current enters the bath is termed the *anode*, while that by which it leaves is called the *kathode*. The solution is called an *electrolyte*. If the current be made to pass through this bath by inserting it in the gap caused by cutting the wire and making the cut ends of wire touch the electrodes, one of the copper plates will be found to increase in weight and the other to decrease by an equal amount ; the one that gains in weight is having copper deposited upon it from the solution, or, as it is often termed, is being copper-plated, while the other is having copper torn off it by the current to make good, so to speak, the loss of copper in the solution by the deposit on the other plate. This effect is in reality only a variety of those referred to under *a*, *b*, and *c* above, and will be dealt with in fuller detail further on

The most obvious question which the student of nature would ask apropos of these facts is, "What is the relation between these numerous phenomena, which we lump together as 'the effects of an electric current,' hiding our ignorance under a well-sounding phrase ?" The only answer that can be afforded to this question is to be obtained by experiment. If we connect together a wire of some length, coiled so that it can be immersed in oil, another wire stretched in air, a third coiled round a rod of iron, and an electrolytic bath, so that the four form one circuit, we can by sending currents of varying strength through this circuit measure the heating effects in the oil bath, the magnetic effects of the wire in air, those of the wire round the iron, and finally the chemical effects in the electrolytic bath. In order to produce currents of varying strength, we may employ a varying number of voltaic cells to assist one another in driving the current. Such an arrangement is indicated in Fig. 1, where *a a a* represent the voltaic cells, *b* the oil bath containing the coiled conductor and a thermometer *c* to measure its temperature, *d* the wire in air, *e* the wire coiled round the iron bar *f*, and *g* the electrolytic bath; m_1 and m_2 are compass needles to measure the magnetic effect of the wire in air and the wire round the iron respectively. The details of such an experiment need to be very carefully arranged if accurate results are to be obtained, and the results, if accurate, will show that if a current from, say, one cell heat the oil bath 1° C. in five minutes, exert forces of 1 dyne and 400 dynes respectively on m_1 and m_2, and deposit ·1 of a gram of copper at *g*, then a current capable of heating the oil bath 2° C. in five minutes will only exert 1·4 dynes at m_1 and deposit ·14 of a gram of copper at *g*. If the current be strong enough to deposit ·2 of a gram of copper in five minutes at *g*, the force at m_1 will be 2 dynes, but the heat developed at *b* will be enough to raise the temperature 4° C. in five minutes.* The forces indicated at m_2 may be varied between very wide limits in the last two cases by varying the conditions, even though the value 400 be always obtained with the first of the three current strengths. The two conditions principally affecting the variation of the force at m_2 are the number of coils of the coiled wire and the size of the piece of iron. These might well be such that the second current produced a force of 560 dynes, and the third a force of 600 or so. This experiment clearly shows that the effects are not proportional to one another by any means. In fact, it is found that the magnetic effect in air and the rate of production of chemical

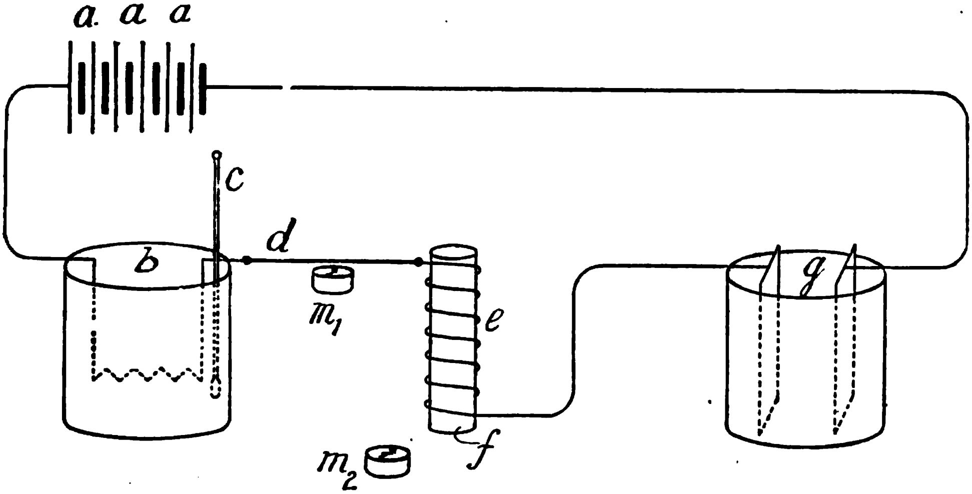


FIG. 1.—MEASURING THE EFFECTS OF AN ELECTRIC CURRENT.

---

* The forces are said to act on m_1 and m_2 for the sake of simplicity. Properly speaking, the forces acting on both the poles of each compass needle should be considered, and if the forces at work on the poles of the needle m_1 are to be compared with those acting on the poles of m_2, the two compass needles must be of identically the same strength and length, or their relation must be known. The dyne is a unit of force of the magnitude of roughly one 1,000th of a gram weight, or one 500,000th of a pound weight.

effect are proportional to one another, and that if we take the chemical effect (say, the rate of deposit of copper) as our standard by which to measure the current, then the magnetic force in air is proportional to the current, and the heating effect to the square of the current. The magnetic effect when iron is present is altogether too erratic to form a suitable basis for the measurement of current, and the reader is referred to Sec. IV. for further information on this point.

If, on the other hand, we take the heating effect as our measure of current, we shall have the magnetic and chemical effects proportional to the square roots of our chosen current strengths. Now, the heat collected *in the oil bath* depends clearly on the length of the wire immersed, there being the same amount of heat generated in every inch, and, further, the opposition of the wire to the current—*i.e.* the electrical resistance of the wire—also depends on the length of the wire, for the resistance of any one inch of the wire is exactly the same as of any other inch of the same wire. It would appear then that, since the total resistance to be overcome depends upon the length of the wire, the amount of E.M.F. necessary to overcome this opposition will also be proportional to the length of the wire ; and since, as we have just seen, the heat developed in the bath will be proportional to the length of the wire immersed, it is clear that the heating effect depends in some way on the E.M.F. involved, and not merely upon the current, for the same current flows through the wire in the bath, no matter how much of it is immersed. On the other hand, the weight of copper deposited is independent of the dimensions of the bath (so long as it is not too small), and therefore also of the E.M.F. involved. For this reason the heating effect has not been accepted as a criterion of the strength of the current, the chemical effect having been chosen in preference. In practice, the magnetic effect in air is by far the most convenient to use, and is very commonly employed as a standard for reference.

WORK, ENERGY, AND POWER.

In these days of electric trams and railways and when electric motors are used so largely for industrial purposes, the thought of power in connection with an electric current is familiar to everyone. The engineer, however, is bound to be very precise in his terms, and it is necessary here to explain the terms that he uses. He has taken words in everyday use rather than coined new ones, and has invested them with extremely precise meanings, the understanding of which is essential to the intelligent perusal of any book on engineering subjects. Two terms in very common use in electrical engineering are "power" and "work." Every errand boy who pushes a hand-truck along the road knows full well that, apart from any question of uphill or downhill, the work he has to do will depend upon two factors, and only upon two, namely, the force with which he has to push his truck, and the distance he has to push it. These facts the engineer expresses by saying that the two factors of work are force and distance, and that the work in any case is given by the force multiplied by the distance. This idea is so simple as to need no further elucidation beyond saying that a unit named the foot-pound is in use for expressing amount of work, the foot-pound being the amount of work done when a force equal to the weight of a pound is exerted through the distance of a foot. A force equal to a quarter of a pound exerted through a distance of four feet amounts clearly to a foot-pound also.

Energy is generally defined to be the capability for doing work, and it can therefore only be measured as work, either as work done or as work capable of being done. The terms energy and work are very largely interchangeable. With the idea of power, as an engineer understands power, people are far less familiar. The engineer defines power as the rate of doing work, a very useful unit having been provided by Watt, who, after experiment, concluded that a horse was capable of doing continuously 33,000 foot-pounds of work per minute, and this rate of doing work is now universally known as one horse power. It cannot be too carefully insisted upon, in view of the frequency of error on this point, that power is *rate of work*. The merest child can do 33,000 foot-pounds of work, or any other amount of work, if you will but give it time enough. On the other hand, a man at his best, and for a very short time, may do considerably over 1 H.P. without doing 33,000 foot-pounds of work at all. An interesting example of this may be given. A man weighing 150 pounds may run upstairs for a short distance at the rate of 6 stairs a second, each stair having a nine-inch rise. He will be found to be working at the rate of very nearly 1·25 H.P., but of course such a rate could not be long maintained, and if maintained for 20 seconds represents a total of 90 ft. × 150 lb. = 13,500 ft. lb. of work.

Since work can be done by an electric current, we can clearly have work and power in connection with an electric circuit, and it is only reasonable to expect that either of these quantities may be calculated for a particular circuit when the details of the circuit are known. This is the case, and although it is not difficult to show from quite elementary considerations how this may be done, the explanation is deferred until Sec. V., and for the present the results only are given.

The rate of working of an electric circuit, or in other words the power in the circuit, is given by the product of current and E.M.F., and consequently the total work done in a given time is obtained by multiplying this product by the time. A concrete case will be useful to fix our ideas. The names given to the units of electrical pressure (or E.M.F.) and of current are *volt* and *ampère* respectively, and consequently a current of 4 amperes driven by a pressure of 5 volts represents 20 units of power. Since the unit of power corresponding to 1 ampere at 1 volt is a useful unit, it has been given a name. Its value is the $\frac{1}{746}$th of 1 H.P., and its name is the *watt*. We thus see that 7·46 amperes at 100 volts = 746 watts, that is 1 H.P. It must be very clearly borne in mind that the watt and the H.P. are merely different sized units for measuring identically the same physical quantity, just as the foot and the yard are merely different sized units for measuring one and the same physical quantity, viz. length. The same length measured in feet and in yards would be numerically represented by two numbers, one of which is three times as great as the other, and the same power may be represented in terms of the watt or of the H.P., only the number expressing the power in watts will be 746 times as great as the number expressing it in H.P. A convenient unit in very common use is the *kilowatt*, which, as the name implies, is 1,000 times as great as the watt. Another unit which must be mentioned here is a unit of work equal to the work done in one second by a power equal to one watt. The name given to this unit is the *joule*. A joule is about 0·737 foot-pounds.

CONDENSERS

In addition to what may be called the continuous flow of a current through a circuit, there is another set of phenomena due to what is known as the capacity of the circuit. These capacity effects are interesting but somewhat unimportant where steady currents are under consideration, but they become enormously important where varying currents, and in particular oscillating currents, are being dealt with. In the light of the single-fluid theory, electricity, when a current is flowing, is being conveyed continuously in one direction through the circuit by the conductor. In order that this flow may occur, it is essential that the circuit should consist of a complete conductor or series of conductors. At first sight it would appear, therefore, that if the continuity of the circuit be broken anywhere, there will be no current, and therefore no phenomena to be observed. Neither of these conclusions is entirely correct. It is both usual and helpful to compare the electric circuit with a hydraulic one, the hydraulic circuit consisting of a complete ring of piping in which a centrifugal pump, representing the cell or source of E.M.F., is inserted. The whole must be imagined to be entirely filled with water. This is indicated in Fig. 2, where *a* is the pipe line, and *b* the centrifugal pump, the cover of which is supposed to be removed and part of the pipe line to be broken open. When the pump revolves, it exerts a "water motive" force and drives the water round the circuit against the frictional resistance of the pipes. If the pipe line be cut at any point, the water will, of course, all run out, and we get a state of affairs which does not exactly

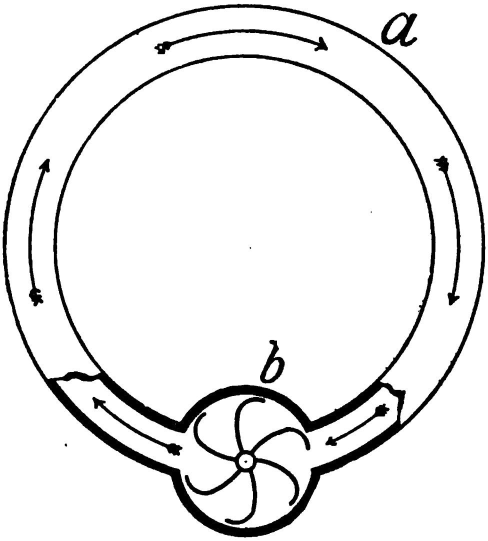


FIG. 2.—ILLUSTRATING THE FLOW OF A CURRENT IN A CLOSED CIRCUIT.

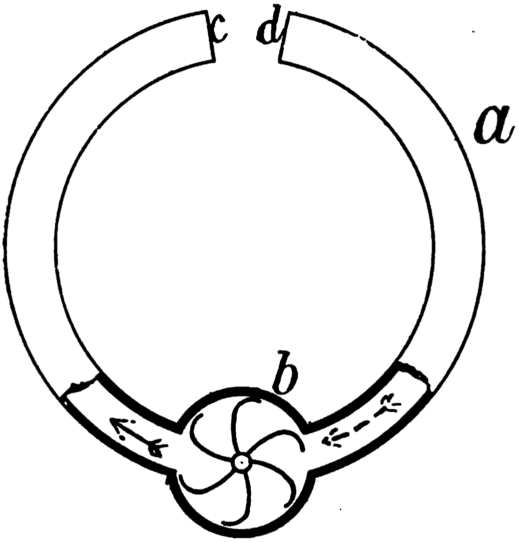


FIG. 3.—ILLUSTRATING AN E.M.F. IN A BROKEN CIRCUIT.

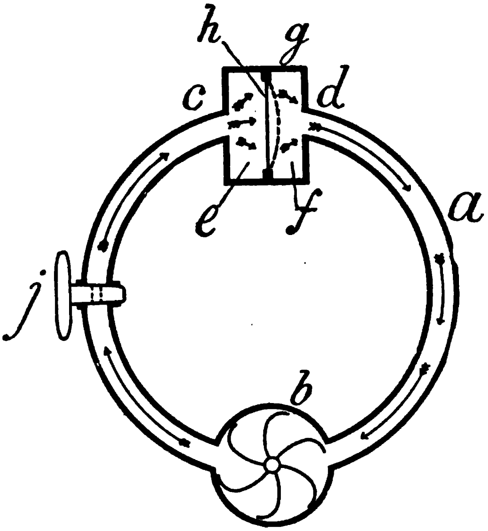


FIG. 4.—ILLUSTRATING THE EFFECT OF CAPACITY.

correspond to anything electrically. If we cut the copper wire of the simple circuit we have been considering, the flow is, of course, stopped, but the electricity cannot all leak away anywhere, as the water in the hydraulic analogue could. The hydraulic analogue is incomplete. When the copper wire is cut, the two ends produced by the cutting are instantly sealed electrically by the air, which is a non-conductor, and to represent this we must suppose the process of cutting the pipe to be accompanied by an instant sealing of each pipe end at the cut. If the pump keeps on working, there is a pressure against the seal at *c* (Fig. 3) tending to force it off, and a suction effect at *d* tending to suck in the seal there. Still our analogue is not very good, and may be much improved if we interrupt the hydraulic circuit in the manner indicated in Fig. 4, where the cut ends *c* and *d* are made to communicate respectively with the two chambers *e* and *f* of a sealed vessel *g*, across the middle of which is an elastic diaphragm *h*, of rubber say, which completely prevents the passage of water from one chamber to the other. The effect of this will be clearer if we suppose a stop-cock inserted somewhere in the circuit, say at *j*. Suppose this stop-cock to be closed before the pump is set to work. The diaphragm will not be distended in any way if the pump be not at work, and after the pump has been started the stop-cock effectually prevents any displacement of the water. If it be now opened, however, there will be a tendency for the water to flow in the direction of the arrows, and, *just at the instant when the stop-cock is opened*, there will be a ***momentary rush*** of water owing to the "stretchability" of the diaphragm. Obviously the flow stops directly the diaphragm has stretched sufficiently to exert a back pressure just equal to the forward pressure of the pump, or, to speak more accurately, when the back pressure of the diaphragm is equal to the algebraical difference between the forward or positive pressure in the chamber *e* and the suction or negative pressure in the chamber *f*.

Supposing the rubber to have stretched to the position shown in dotted lines, it will be clear that, since the only effect has been a displacement of water round the whole circuit (water being practically incompressible), if a pint of water has been forced into the chamber *e*, owing to its now enlarged condition, exactly a pint will have been displaced from *f* in its now diminished volume. Observe that rubber is a non-conductor of water, but that it possesses the property of yielding, to a certain extent, under a "water-motive" force. Non-conductors of electricity possess precisely this property in reference to electricity, and when the continuity of an electric circuit is interrupted by the presence of a non-conductor or dielectric, the dielectric yields to a certain extent under the stress of an E.M.F., if one be present, and just at the instant of application of that E.M.F. there is a momentary current in the circuit corresponding to the displacement or rush of electricity throughout the circuit.

An instrument specially designed to exhibit this dielectric elasticity is called, or rather miscalled, a *condenser*, and its power of yielding under a given voltage is called its *capacity*. The idea underlying this term is that the capacity of an electric condenser corresponds to the capacity of what I must call the "hydraulic condenser" *g* (Fig. 4) to permit of displacement of water. For example, if it would permit of a displacement of 8 pints of water for every [illegible] lb. of difference of pressure between the sides *e* and *f*, it might be said to have a capacity of 8, and this statement would at the same time give a unit for the measurement of capacity.

A condenser is said to have unit capacity if a voltage of one volt applied to it will displace one *coulomb*. (*See* Sec. V.)

CHAPTER II.—CONDUCTORS.

EFFECT OF DIMENSIONS—MATERIALS—METALS AND IMPURITIES—EFFECT OF TEMPERATURE—ALLOYS—ELECTROLYTES—INSULATORS.

EFFECT OF DIMENSIONS.

It has already been stated that the copper wire of our simple circuit possessed the property of offering a kind of opposition to the passage of a current of electricity. The name given to this property is *resistance*, and it remains to be seen how the resistance of a conductor is affected by its dimensions, its material, and its temperature.

Taking the effect of the dimensions first into consideration, it is found that the resistance of a conductor is proportional, *cæteris paribus*, to its length. This is what might be anticipated without experiment by considering, as we have already pointed out, that the resistance of any one piece of wire would doubtless be equal to that of an exactly similar piece, and that the resistance offered to the current in passing successively through two such lengths placed end to end would presumably be double that offered by one length, and so on for any number of lengths. Experiment fulfils this anticipation, and it is found that the resistance of a conductor is strictly proportional to its length.

It must be carefully observed that the two or more lengths just referred to are supposed to be placed end to end, but that nothing has been said as to the effect of placing a number of lengths side by side, like a bundle of sticks, with all their adjacent ends touching one another. This can best be dealt with by considering that property of the conductor given mathematically by the reciprocal of the resistance, and representing physically, therefore, the converse of a resistance, or what may be termed the *easiness* with which the conductor permits the passage of a current. This is known as the *conductance* of a conductor. Lengths of conductor placed end on are said to be in series, and the side by side arrangement is known as parallel grouping, or the lengths are said to be in parallel. In older books the terms "in multiple," "in multiple arc," and "in parallel arc," will sometimes be found in place of the now commonly used term "in parallel." If we take a number of equal lengths of the same wire and put first two, then three, then four side by side in parallel, it would be reasonable to expect that the path for the current from one point in space to another, when the distance between the points is bridged by two of the lengths in parallel, would be twice as easy as when there is only one, and that three in parallel would afford a path of three times the easiness of one length. Such an anticipation is fulfilled by experiment, and we find that the total conductance of a number of conductors in parallel is the sum of the individual conductances, just as the total resistance of a number of conductors in series is the sum of the individual resistances.

In the light of what has just been said, we will consider the effect on the conductor of its size, that is to say, of its cross-sectional area. It is an obvious step to regard a conductor whose section is, say, 1 in.

by 1 in. as being made up of sixteen square conductors each $\frac{1}{4}$ in. by $\frac{1}{4}$ in. conglomerated together; or as being made of 64 conductors each $\frac{1}{8}$ in. square, or of 100 $\frac{1}{10}$ in. square. From this it is clear that the conductance of the conductor whose sectional area is 1 sq. in. is 16 times as great as that of the conductor $\frac{1}{4}$ in. square having a $\frac{1}{16}$ of a square inch sectional area, or, to put it generally, the conductance of a conductor is proportional to its cross-sectional area. Its resistance will consequently be inversely proportional to this dimension, and combining this with our former result we find the resistance of a conductor to be proportional to the length divided by the area, or

$$R \propto \frac{l}{a},$$

where l is length and a is area of cross section.

MATERIALS.

The influence of the material of which it is composed on the resistance of a conductor has now to be considered, and here we are face to face with physical properties of materials for which at present we have no explanation. The resistance at a given temperature of a conductor of given dimensions depends entirely upon the material of which it is composed, and this is expressed by saying that each material has its own specific resistivity. For example, copper conducts better than iron, but not so well as silver, while the resistance of mercury is about sixty times as great as that of copper. No reason can be assigned for these facts, any more than a reason can be given for the fact that copper is lighter than lead, or that aluminium is lighter than copper. These facts are conveniently expressed by saying that the *specific gravity* of each material has a certain value. The specific gravity of a material is, of course, merely the weight of a definite volume, and we are thus led, by analogy, to define the *specific resistivity* of a material as the resistance of a conductor of definite dimensions, made of that material. The unit in terms of which resistance is measured is called the *ohm*, but we must refer the reader to Sec. V. for a fuller account of this unit.

The standard dimensions of the conductor, the resistance of which represents the specific resistivity of a material, are 1 centimetre each way, that is to say a cube of 1 cm. edge. The resistance is measured from one face to an opposite face, and as the conductor is a cube it is clearly immaterial between which two opposite faces the measurement is made. The measurement is never made on an actual centimetre cube, but on a very much longer conductor whose dimensions are accurately known, from which the resistance of a centimetre cube is calculated. Further, as the resistence of a centimetre cube of any metal is so small as to be only a minute fraction of an ohm, a name has been given to the one millionth part of an ohm to make it serve as a convenient sized unit for this purpose. The name given is the *microhm*, and specific resistivities are given in tables in terms of microhms for a centimetre cube. There is a very common and misleading error of speech to be met with in this connection. People who should know better frequently speak of *the resistivity per cubic centimetre*. In the first place, it is absurd to speak of the resistivity *per* cubic centimetre, because the term *per* ordinarily conveys a meaning which it cannot possibly have here. But in the second place it is a more heinous crime still to speak of resistance as *per cubic centimetre.* A cubic centimetre of copper may have an infinite variety of shapes; for example, any of those given at *a*, *b*, *c* and *d* in Fig. 5, or it may be in the form of a wire, say, 10 metres long and one thousandth of a square centimetre in cross section. A moment's reflection will show that the resistance of the forms *b*, *c* and *d* must all be different from that of the cube *a*, when all are measured between two opposite faces in the direction of the arrows; and, further, each of the forms *b* and *c* will have three different resistances when measured between the three different pairs of opposite faces which each block possesses. Again, the wire just referred to would have a resistance millions of times as great as any one of the blocks shown in Fig. 5. It is thus evident that the resistance of a *cubic centimetre* even of copper may have any value, the only limits being, in the one direction, the fineness to which a copper wire can be drawn, and, in the other, the thinness to which copper foil can be beaten. A centimetre cube, on the contrary, can only have one resistance, and that the same between any pair of opposite faces.

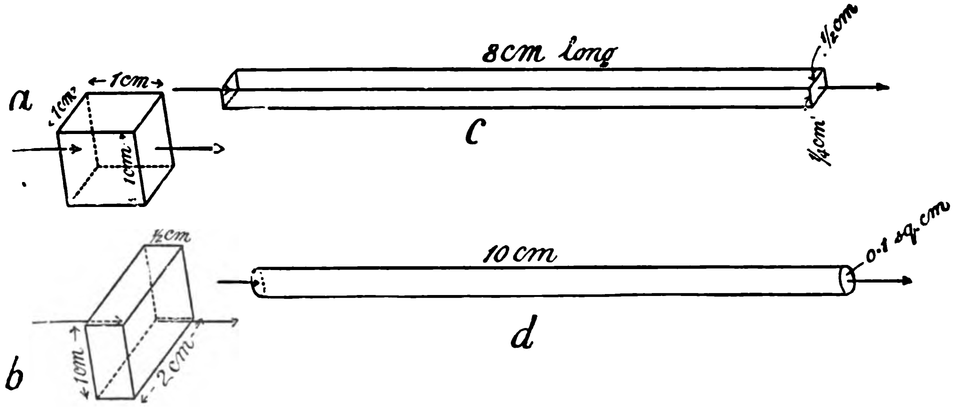


FIG. 5.—ILLUSTRATING VARIOUS RESISTANCES OF A CUBIC CENTIMETRE.

The following list contains the values for the resistivity of the more important metals :—

Metal.	Resistivity in microhms for a one centimetre cube at 0° C.
Silver (annealed)	1·497
,, (hard-drawn)	1·625
Copper (annealed)	1·589
,, (hard-drawn)	1·626
Gold (annealed)	2·050
,, (hard-drawn)	2·085
Aluminium (annealed)	2·899
Platinum (annealed)	9·010
Iron (annealed)	9·66
Nickel (annealed)	12·40
Mercury (liquid)	94·61

The above figures relate to practically pure metals, and the values will be very considerably altered by the presence of appreciable impurities. It will be noticed, too, that any hardening process tends to increase the resistivity, whereas a softening or annealing process invariably reduces it.

EFFECT OF TEMPERATURE.

The resistivity of a metal invariably rises with an increase of temperature, and hence where great accuracy is required it is very important to know the temperature at which a conductor will have to work. Between the limits of temperature which commonly occur, the change of resistance is strictly proportional to the temperature change. The actual increase is also proportional to the original resistance, and for a given change of temperature the change of resistance of a conductor may be expressed as a percentage of the resistance at the lower temperature. It thus becomes convenient, when comparing this property for different materials, to reduce it to one common basis, that chosen being the percentage increase per 1° C. rise of temperature. This quantity is called the *temperature coefficient of resistance* for the material, so that if the temperature coefficient of copper is said to be 0·388, it means that a copper conductor of 100 ohms resistance at 0° C. will, when warmed to 1° C., have a resistance of 100·388 ohms. It is clear that the increase of resistance is not due to the expansion of the metal producing a change in the dimensions merely, since any increase in length due to heating is accompanied by an increase in cross-sectional area. In fact, the increase in area due to expansion occurs at a greater rate than the increase in length, and on this score the resistance should decrease. The change in resistance is a physical property apparently quite independent of the coefficient of expansion.

ALLOYS.

It will be seen, in the chapter dealing with instruments and testing, that it is very desirable to have a conductor whose resistance will not change with temperature, and many efforts have been persistently made to obtain a material which shall fulfil this condition. It was early found that alloys possessed in general a lower temperature coefficient than their constituents, and it became a matter of simple experiment to discover an alloy which should possess a negligible temperature coefficient. The two earliest, and two which held the field for a very long time, were platinum silver and nickel silver, or, as it is commonly called, German silver. A difficulty much met with in the case of alloys containing iron, and in some other alloys, was a tendency to become extraordinarily brittle, even to the point of crumbling to pieces. In other words, many of the alloys tried did not prove stable, and others proved extremely susceptible to the least traces of acid, even to the acid to be found in commercial paraffin wax. Messrs. Feussner and Lindeck have also shown that alloys made without zinc are more reliable than those with it. A valuable feature of nearly all the alloys is their high resistivity. The subjoined list contains particulars of the more important alloys and materials in present use, including platinum silver and German silver, which, however, are being rapidly superseded for accurate work. Any special treatment required in the case of particular materials is dealt with in the chapter on instruments.

MATERIAL.	MICROHMS PER CENTIM. CUBE.	% INCREASE PER 1° C.
Platinum silver	24·2	0·026
German silver ...	20·8	0·036
Platinoid... ...	32·0	0·02
"Eureka" ...	42·0	0·04
"Manganin" ...	47·5	± ·001
"Rheostene" ...	34·3	0·015
"Constantan" ...	51·0	± ·001
Krupp metal ...	85·0	0·7
Carbon	1·16 × 10^4	− 5·0 to − 3·7
Iron	9·6	0·45

The figures above are approximately correct only, and will serve for estimates of material required.

ELECTROLYTES.

The conducting power of an electrolyte is at present regarded as being due to the power of the water or other solvent to break the dissolved salt up into ions of two kinds, with one of which are associated positive charges, and with the other negative charges.

A "charge" of electricity may be regarded as being a surplus or deficit according as the charge is positive or negative. An uncharged body may be regarded merely as one possessing the normal amount of electricity, and if that normal amount be disturbed (see p. 2) the body becomes positively charged if the disturbance results in an access, or negatively if the result is a removal, of electricity.

The electrodes in an electrolyte are maintained also in a charged condition by the battery to which they are connected, the anode (see p. 6) being positively and the kathode negatively charged. Between two oppositely charged bodies there is what is called a "field of electric force," which is merely a way of expressing, among other things, the fact that a charged body, introduced into the field, will experience a force urging it in a direction to one or the other fixed charged bodies. If the body introduced into the field be positively charged, it is urged toward the negatively charged body, and *vice versâ*.

The two kinds of ions therefore travel under the influence of the field of electric force in opposite directions through the solution. Those which travel towards the cathode, as the electrode or plate by which the current leaves the solution is called, are called *cations*, and those which travel in the opposite direction, that is towards the electrode called the anode, are called *anions*. The cations are associated with positive electrons—*i.e.* are positively charged—and the anions are associated with negative electrons or are negatively charged. If the direction of motion of the cations be considered positive, that of the anions will be negative, and the current is thus considered as only flowing in one direction, since negative electrons moving in a negative direction must clearly be regarded as producing a positive effect.

It is customary to regard electrons as being charges of negative sign, and a positive ion or cation is an ion deprived of a negative charge or electron and thus rendered positive; while an anion is the atom together with its electron, the combination of the two being of negative sign.

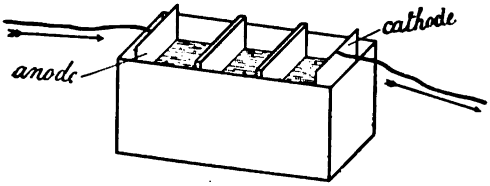


FIG. 6.—VELOCITIES OF CATIONS AND ANIONS

A most interesting discovery, due mainly to the labours of Hittorf between the years 1853 and 1859, is that when a current passes through an electrolyte the anions and cations do not move with equal velocities. The old view which was tacitly held until then was that equal numbers of anions and cations passed in opposite directions through any section of the electrolyte in a given time, the motion of a charged body being regarded as constituting, as we have already seen, a flowing current. In point of fact, the relation between the two velocities may be one of great inequality For example, when a solution of hydrochloric acid is electrolysed the hydrogen ions, which are the cations, move five times as fast as the anions, the chlorine ions.

This accounts for the fact that if such a solution be placed in a vessel which is divided by porous partitions into three compartments, and electrolysed, an alteration in the concentration of the acid takes place. At the start equally strong acid is placed in all three compartments, but after being electrolysed for some time the solution in the cathode compartment (Fig. 6) is found to be richer in acid than that round the anode, and the ratio of the loss in strength at the cathode to the loss at the anode gives the ratio of the velocity of migration of the anions to that of the cations. This may be seen as follows. Let a given "quantity" of electricity have passed through the bath during the electrolysis. The result will be the liberation of a definite weight of W gramme-equivalents of hydrogen at the cathode and W gramme-equivalents of chlorine at the anode.* Now, if the hydrogen ions move five times as fast as the chlorine ions, five-sixths of the electricity will have been carried by the hydrogen ions as a positive charge in a positive direction (*with* the "current"), and one-sixth by the chlorine ions as a negative charge in a negative direction (*against* the "current"). This is equivalent to saying that $\frac{5}{6}$ W gramme-equivalents of hydrogen migrate to the cathode chamber, and $\frac{1}{6}$ W gramme-equivalents of chlorine to the anode chamber. The upshot of this is that in the cathode chamber W gramme-equivalents of hydrogen have been liberated (have escaped into the air, let us suppose), $\frac{5}{6}$ W have entered by migration from the anode chamber, and $\frac{1}{6}$ W of chlorine have left and migrated to the anode chamber. There should thus be a loss of W and a gain of $\frac{5}{6}$ W, or a total loss of $\frac{1}{6}$ W of hydrogen ions in the cathode chamber. Also $\frac{1}{6}$ W of chlorine ions have migrated, and thus there is a total loss of $\frac{1}{6}$ W of the two kinds of ions, and on testing for acid we find a loss of $\frac{1}{6}$ W gramme-equivalents of hydrochloric acid. In the anode chamber is a loss of W gramme-equivalents of chlorine ions by liberation, and a gain of $\frac{1}{6}$ W by migration from the cathode, or a total loss of $\frac{5}{6}$ W; there is also a loss of $\frac{5}{6}$ W gramme-equivalents of hydrogen by migration to the cathode, and hence a total loss of $\frac{5}{6}$ W gramme-equivalents of hydrochloric acid. The ratio of the losses is as 1 : 5, which is the ratio of the velocities of the ionic migrations. In the middle chamber no gain or loss occurs; it serves merely as a connecting link between the cathode and anode chambers to afford a passage for the ions, and therefore for the current. Liberation of the ions, that is in this case escape into the air, only occurs *at the electrodes*, not in the mass of the liquid.

---

* A gramme-equivalent is a measure of mass used in chemistry, and is for a given substance the mass of it whose weight in grammes is chemically equivalent to 1 gramme of hydrogen; that is, the number of grammes which can displace, or be displaced by, one gramme of hydrogen.

It must be understood that what is referred to above as the power of the solvent to break up the salt into ions is quite distinct from the amount of salt in solution. In fact, for any except very dilute solutions, the solvent does not break up more than a portion of the salt it dissolves, the proportion depending on the concentration of the solution. The breaking up into ions is known as electrolytic dissociation, and the proportion of the dissolved salt dissociated is known as the degree of dissociation. Strictly speaking, a salt is only entirely dissociated when it is in an indefinitely dilute solution; but in practice, when considerable dilution has been reached, any further dilution has no appreciable effect. The specific resistivity of an electrolyte is the same property as the specific resistivity of any other conductor, but the knowledge of it is of less value; the resistance of electrolytes varies very much with variations in temperature, it being commonly of the order of 2½ per cent. per 1° C. Moreover, for ordinary cases, that is for unsaturated solutions of acids, alkalies, and binary salts, the coefficient for resistance is negative; that is to say the resistance *decreases* with an *increase* of temperature. The reason why it is not of much use to speak of the specific resistance of electrolytes is that their resistance depends so little on the actual dimensions, and so greatly, as has just been stated, on the degree of dissociation. It is further much more convenient to speak of the reciprocal of the resistance, that is of the conductivity, in the light of the part played by the movements of the dissociated ions. Since the conductivity of an electrolyte is thus so dependent upon its content of dissociated ions, and this in turn depends upon the concentration or dilution of the solution, it has been found necessary, for purposes of comparison, to consider the conductivity of a solution containing a standard quantity of the material.

The standard quantity taken is the gramme-equivalent, and a solution containing this is imagined to be placed between two flat parallel electrodes of indefinite extent, placed one cm. apart, and the conductivity of the whole solution is called the "equivalent conductivity." If the gramme-equivalent be contained in a cubic cm. of solution, and this be placed between the electrodes, the equivalent conductivity will clearly be the same as the specific conductivity, since the solution must then provide a path one cm. long and one sq. cm. in area. If now the solution be diluted to a bulk of 500 cubic cm., the whole of the bulk must be introduced between the electrodes in order that a gramme-equivalent of the dissolved salt may take part in the conduction. The cross-section of this solution, when between the electrodes, will of course be 500 sq. cm., and the equivalent conductivity therefore 500 times as big as the specific conductivity (of this more dilute solution), which is that of a path having one sq. cm. area of cross-section. This latter specific conductivity is not the same in value as was the specific conductivity of the more concentrated liquid, and if we denote by K the equivalent conductivity of a solution containing a gramme-equivalent per cubic cm., and by S its specific conductivity, then

$$K = S.$$

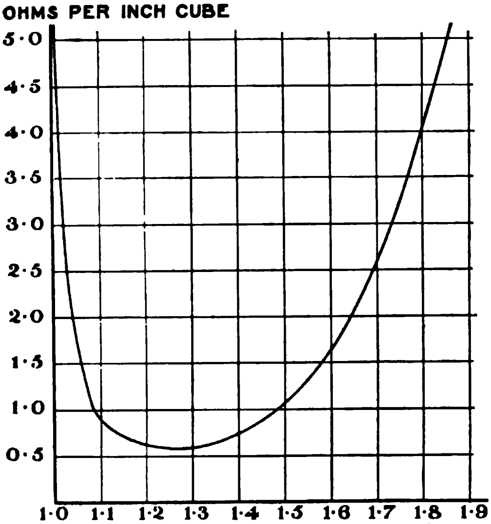


FIG. 7.—RESISTIVITY OF SULPHURIC ACID.

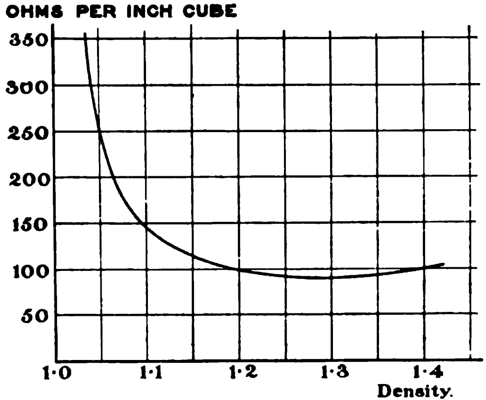


FIG. 8.—RESISTIVITY OF ZINC SULPHATE SOLUTION.

If further we denote the degree of dilution by *d*, so that *d* represents the number of cubic cm. containing a gramme-equivalent, then

$$K' = d \times S',$$

where K′ and S′ stand for the equivalent and specific conductivities respectively for the solution whose dilution is *d*.

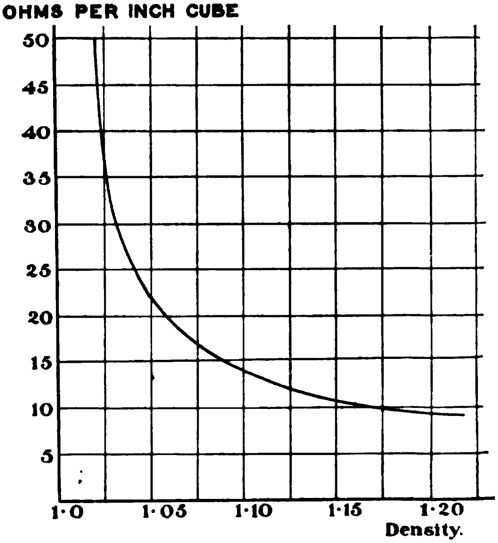


FIG. 9.—RESISTIVITY OF COPPER SULPHATE SOLUTION.

In the case of dilute sulphuric acid it will be seen by examination of the annexed curve Fig. 7 that the specific conductivity does not change steadily as dilution proceeds. In Figs. 8 and 9 are given similar curves for zinc sulphate and copper sulphate respectively as determined by the author.

It has already been seen that the ratio of the losses at cathode and anode is that of the velocities of anion and cation ; or

$$\frac{\text{loss at cathode}}{\text{loss at anode}} = \frac{v_A}{v_C}$$

It is usual* to express the weight of anions which passes from cathode to anode as a fraction of the weight of liberated anions or cations expressed in gramme-equivalents. Then, if p is this fraction, $1-p$ is the corresponding value for the cations, and

$$\frac{p}{1-p} = \frac{v_A}{v_C};$$

$$\text{also } p = \frac{v_a}{v_a+v_c}$$

$$\text{and } 1-p = \frac{v_c}{v_a+v_c}$$

Kohlrausch showed in 1879 and 1885, in contributions to Weidemann's *Annalen*, that the total conductivity of a binary electrolyte is the sum of the conductivities of the ions, and these being regarded as due to the velocities of the ions it is clear that the relative conductive effects are proportional to the relative velocities. Hence, if we measure the equivalent conductivity when a high degree of dissociation has been obtained, and so obtain the value of the total conductive effects, we can get the individual velocities expressed in conductivities.

All that is needed is to get three ions which can form two compounds and make the measurements on both ; for example, hydrochloric acid and common salt (HCl and NaCl) may be used. Expressed in symbols used above, the reasoning is

$$K = q\left(v_a + v_c\right)$$

where q is a numerical factor ; but since

$$\frac{v_a}{v_a+v_c} = p,$$

$$q\,v_a = p\,K$$

$$\text{and } q\,v_c = (1-p)\,K,$$

then to express the velocities of migration in terms of conductivity we can write the factor $q=1$.

INSULATORS

Insulators may be regarded as conductors of extraordinarily high resistivity, except in so far as their resistivity decreases, instead of increasing, with an increase of temperature.

All insulators may be said to be poor mechanically in some direction or another, if not in several. Thus, indiarubber is incapable of being turned or filed, or of taking a screw-thread. It has the sole virtue of being tough. Porcelain may be cited as an opposite extreme. It is brittle and can be moulded with a very fair screw-thread, but it is too hard to be tooled in any way after it has been fired, and, moreover, if its shape be altered by grinding the surface glaze is destroyed, and its insulating property thereby enormously diminished. Those materials which have the greatest number of good mechanical properties are either inflammable or hygroscopic, any tendency of a material to absorb moisture rendering it totally unfit for use except in hot or exceptionally dry positions. As examples of this class, ebonite, celluloid, and vulcanised fibre may be cited, the two former being readily turned, drilled, and filed, as well as being readily moulded, but being inflammable, celluloid particularly so. Vulcanised fibre, on the other hand, is very non-inflammable, but extremely hygroscopic. It may, however, be subjected to ordinary mechanical processes, is strong and tough, and thus apart from its hygroscopic properties an excellent material. The following is a list of materials in common use for insulating purposes, together with a brief statement of their leading properties :—

---

* *Lehrbuch der Elektrochemie*, by Le Blanc, p. 57. 2nd ed.

Wood.—Only suitable for low insulation. Inflammable, hygroscopic, easily tooled, mechanically good, but liable to split and warp.

Cotton.—Poor insulator, inflammable, hygroscopic, weak mechanically.

Silk.—Excellent insulator, inflammable, not very hygroscopic, strong.

Paper.—Fair insulator, inflammable, hygroscopic, mechanically weak.

Indiarubber and Guttapercha.—First-class insulators, inflammable, non-hygroscopic, soft, and poor mechanically, also lacking in durability when exposed to atmospheric changes.

Vulcanised Fibre.—Good insulator when perfectly dry, non-inflammable, very hygroscopic, may be well tooled, and is mechanically good.

Asbestos.—Fair insulator, fireproof, hygroscopic, can only be used in the form of fibre, string, or sheet ; mechanically poor.

Vulcanised Indiarubber.—First-class insulator, highly elastic, more durable than pure indiarubber, inflammable, non-hygroscopic.

When the vulcanisation is carried to such a point as to form the substance known as

Ebonite, *Vulcanite*, or *Hard Rubber*, we obtain a material having first-class insulating properties, but inflammable ; absolutely non-hygroscopic, may be perfectly tooled, and having excellent mechanical properties if not overheated. May be moulded or bent to any shape when at the temperature of boiling water.

Glass.—First-class insulator, non-inflammable but not fireproof, has tendency to collect moisture over surface, cannot be tooled, strong but brittle.

Porcelain.—Similar to glass, but superior, being fireproof and having less tendency to collect moisture ; less brittle. Takes also a much better screw-thread.

Mica.—One of the best insulators we have. Absolutely fireproof and non-hygroscopic, unmechanical, but, owing to the extreme thinness in which plates can be obtained, particularly useful in many cases where extra high insulation is desired.

From mica most excellent preparations are made by associating it, either in the form of thin slips or in the form of powder, with other materials which supply the mechanical properties in which it is lacking. The material known as micanite, for example, is made up of thin slips of mica cemented together so as to form either flexible sheets, hard sheets, rods, tubes and rings, etc. Ground mica incorporated with various kinds of clay forms an extremely hard, non-brittle insulating substance employed for overhead work on tramlines.

Oils, *Fats*, *Gums.*—All vegetable and mineral oils, fats, and waxes are excellent insulators, but obviously only suitable in special cases owing to their fluid or semi-fluid properties. The same remarks apply pretty much to gums, and these, as well as the oils, are largely used as varnishes and for impregnating fibrous and other absorbent materials which supply a mechanical basis.

A list is appended giving numerical particulars of a few of the most important materials in common use. Further information will be found in the chapters on cables and on the construction of generators.

MATERIAL.	MEGOHMS PER CENTIM. CUBE.
Air (dry)	Infinity
Mica	$8{\cdot}4 \times 10^{6}$
Glass	$(6{\cdot}0 \text{ to } 100) \times 10^{7}$
Porcelain...	$5{\cdot}4 \times 10^{11}$
Guttapercha	$4{\cdot}5 \times 10^{6}$
Indiarubber	$2{\cdot}5 \times 10^{7}$
Ebonite	$2{\cdot}8 \times 10^{10}$
Shellac	$9{\cdot}0 \times 10^{9}$
Paraffin wax	$3{\cdot}4 \times 10^{10}$
Paraffin oil	${\cdot}8 \times 10^{6}$

CHAPTER III.—SIMPLE AND COMPLEX CIRCUITS.

A "LAW"—OHM'S LAW—RESISTANCES IN SERIES AND IN PARALLEL—CELLS IN PARALLEL AND SERIES—POTENTIAL AND POTENTIAL DIFFERENCE—FALL OF POTENTIAL—APPLICATIONS OF OHM'S LAW—SIMPLE AND COMPLEX CIRCUITS.

A "LAW."

THE term "a law of nature" has unfortunately become so common a catchword that many people who speak freely of the laws of science have little comprehension of the true meaning of a scientific law. Nature is in no sense bound by what men are pleased to term her "laws." All that can be said of a so-called law of nature is that men have found certain natural phenomena to occur, in all observed cases, in a definite sequence, or in definite relative proportions. The result of these repeated observations is then, and with reason, regarded as certain, and is expressed either in one or more sentences, or perhaps more briefly and easily in a mathematical equation. This equation, or the words which take its place, is then called the "law" of the phenomenon, but it cannot be too carefully borne in mind, particularly by the student, that it is nothing more than a brief expression of a sequence or of a proportion that has hitherto invariably been found to hold good, and may reasonably be expected always to hold good under the precise conditions which were in force during the observations. A further point to be most carefully borne in mind is that the truth of all our "laws" rests entirely upon the possible accuracy of observation or measurement attainable. This accuracy may be affected by the delicacy, or want of it, of the instruments, and by an enormous variety of conditions too numerous to be specified. It is readily conceivable that an observer equipped with insensitive instruments might obtain results leading him to infer that the two quantities he was studying were proportional to one another, whereas better instruments would have enabled him to discover a very significant and regular, though small, departure from proportionality. One of the commonest of errors in the application of a law is to apply it to cases beyond the range of the experiments or observations by which it was originally established. This may readily be exemplified by reference to what is known as Boyle's law. Boyle's law stated that for what was called a perfect gas, if the temperature were kept constant, the volume would vary inversely as the pressure. This is true within the ordinary range of temperature and up to fairly large pressures, but the law breaks down when applied without discrimination to extremes of temperature or extremes of pressure. Again, the law we are about to discuss is not applicable, *as it stands*, to all circuits, although it is essentially true of all. It has to be restated for circuits carrying varying currents.

OHM'S LAW.

Professor George Simon Ohm, in the early part of the last century, about the year 1830, deduced from theory a "law" which has ever since borne his name. The law in question is a statement of the relationship between the three fundamental properties of an electric circuit, viz. its resistance, the E.M.F., and the current through it. Professor Ohm concluded that if the resistance of a circuit were constant, the rate of flow of electricity, or the current, would be directly proportional to the E.M.F. at work, or that, to produce a given current in a circuit, the E.M.F. necessary would be proportional to the resistance of that circuit. Most briefly stated, the law is

$$E \propto C \times R,$$

where E, C, and R, represent the E.M.F., the current, and the resistance respectively.

Professor Ohm, and subsequently Professor Daniell, set to work to confirm this experimentally, and as a result of their magnificent labours this law, which may be said to have laid the foundation of the experimental science of current electricity, has for long been regarded as unassailable. It will be noticed that in the above statement we have only the sign of proportionality, and obviously it will be a great step if we can substitute that of equality. To merely state that the price of a load of sugar is proportional to its weight is not of much value. But to say that the price of a load is equal to the weight *measured in cwt.* multiplied by eight *shillings* is of great use. In order that the necessary steps may be clearly understood, let it be supposed that a hydraulic law had been discovered which stated that for cast-iron pipes the rate of flow of water through a given pipe was proportional to the head or driving pressure, and that to produce a given flow through a 4 in. pipe, the head or pressure required was proportional to the length of the pipe. This law could be written

$$H \propto F \times L,$$

where H is the head, F is the flow. and L is the length. Now this statement might be interesting but not very useful, for it does not tell an engineer who is to supply a house with water from a lake a quarter of a mile away, and 80 ft. above it, how many gallons an hour he can get through a 4 in. pipe. To do this the law must be stated more fully; that is the quantities must be stated in terms of known units, and the sign of equality substituted for that of proportionality. The flow through such a pipe would, in fact, be roughly 200 gallons a minute, but we clearly cannot write the head in feet and the length in miles and the flow in gallons per minute, and then use the sign of equality, for that would read $80 = 200 \times \frac{1}{4}$, which is nonsense; and we must find some unit or units which will fit. We are not bound to express the pressure as a head of so many feet, so we will take for our unit of pressure 1 lb. per square inch, and keep our measurements of rate of flow as before; that is, the unit to be 1 gal. per minute. We shall now find that if we take for our unit of length, not a mile, as in the equation that did not hold, but a length of 7,610 ft. of 4 in. pipe, the equation can be properly written. Yet one more step. Let us give names to these units. The result may look a little ludicrous, but will be instructive. We will call our unit of pressure the "pinch." (This is merely *our name now* for "one pound per square inch.") We will call the *gallon per minute* the "gam," and our unit of length the "rom." Now we can write

$$1 \text{ pinch} = 1 \text{ gam} \times 1 \text{ rom};$$

or, inserting the figures for the case in point, where the pressure was 34·7 pinches and the length

$$\frac{1320 \text{ ft.}}{7610 \text{ ft.}} = 0{\cdot}1735 \text{ roms.}$$

Hence we can write that

$$G = \frac{P}{R} \text{ or gams} = \frac{34{\cdot}7}{0{\cdot}1735},$$

which, on working out, of course gives gams = 200.

It is not difficult to see that the rom is not really a unit of length, but is the frictional resistance of a length of pipe of fixed diameter, viz. 4 in.; in fact, it is the resistance of about a mile and a half of such a pipe.

In precisely the same way, in order that Ohm's law may be expressed *numerically*, we must have properly related units, and clearly it will be sufficient to define arbitrarily two, from which the magnitude of the third will follow necessarily.

The unit of current and the unit of pressure to be employed in practical measurements have been arbitrarily defined, the former as the current which will deposit 0·001118 grams of silver per second, and the latter as the $\frac{1}{1\cdot434}$th of the E.M.F. of a Clark cell at 15° C. Reasons for the choice of these units will be given in the chapter on Units in the section on Testing, where it will be seen that the units chosen rest on a simple and most rational basis, and that the definitions given here are merely to afford a means of practical verification. The actual numbers involved in these practical definitions are therefore unnatural and fortuitous.

The two units given, viz. the ampère and volt, render it unnecessary to define the ohm, except as $= \frac{1 \text{ volt}}{1 \text{ ampere}}$ by Ohm's law. For practical purposes, however, it is convenient to have a standard for reference which will not first involve accurate determinations of the other two. Such a standard is provided by the resistance at 0° C. of a column of pure mercury of uniform cross-section throughout, viz. one square millimetre, and 106·3 centimetres long. The dimensions may be checked by weighing the mercury: it should weigh 14·4521 grammes. This standard is known as the international ohm, and is the now universally accepted standard. It is approximately 1·3 % greater than the old standard known as the B.A. unit, 6·3 % greater than the still older Siemens unit, and about 0·3 % greater than the legal ohm, which it supplants.* The discrepancies between these so-called "standards" are due to the endeavours of scientists to provide an accurate practical standard, in agreement with the practical standards of E.M.F. and of current already given, and these endeavours have resulted in increasing accuracy of the standard, so that we may now consider that finality has been reached, and that the international ohm is the true ohm within the limits of experimental accuracy.

Having determined and named the units, we can use the sign of equality and write Ohm's law thus:—

$$\frac{\text{volts}}{\text{ohms}} = \text{amperes.}$$

Ohm's law is so excessively simple in statement that the danger lies in thinking it too simple to require much attention, whereas in point of fact the author has known scores of students who, at the end of a year's study, can make numerous applications of the law, and perform accurate calculations by its aid, but yet have not grasped its full significance.

The great utility of Ohm's law lies in its perfect generality. It is not merely a statement necessarily having reference to the properties of an entire circuit, but it is broadly and invariably true of the three quantities involved, whether they refer to a part or to the whole of a circuit. All that is necessary in its application is to ensure that the three quantities all refer to precisely the same, or the same part of a circuit. This will be exemplified when we have considered the effect of varying the arrangement of cells.

---

* The Siemens unit was a column of mercury 1 square mm. in section, 100 cm. long; and the legal ohm a similar column, 106 cm. long.

RESISTANCES IN SERIES AND IN PARALLEL.

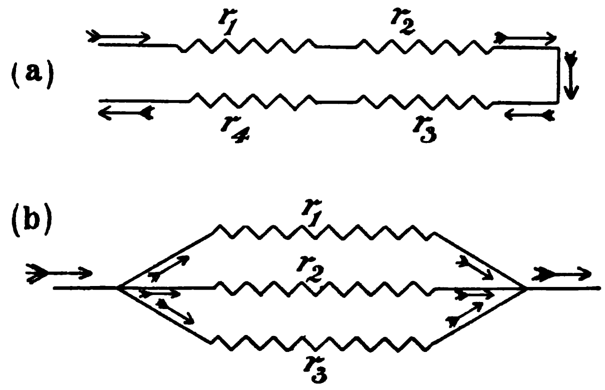


FIG. 10.—CONDUCTORS IN SERIES AND IN PARALLEL.

The effect on the resistance of a number of conductors brought about by arranging them in series or in parallel has been referred to briefly on page 12. It was there stated that when conductors are placed in series their total resistance is equal to the sum of the individual resistances, and that when placed in parallel their resistance could be arrived at by considering the fact that their total conductance was equal to the sum of the individual conductances. No application was made of this beyond the case of conductors of equal resistance, but the principle is widely applicable, and must be stated in a general form.

In Fig. 10 four conductors, r_1, r_2, r_3, and r_4, are diagrammatically shown connected "*in series*" at (a), and three are shown at (b) "*in parallel*," the arrows indicating the path of the current.

If we have a number of conductors whose resistances are r_1, r_2, r_3, r_4 etc., respectively, and their conductances k_1, k_2, k_3, k_4 etc. then we have the relationships

$r_1 = \frac{1}{k_1}$, $r_2 = \frac{1}{k_2}$, $r_3 = \frac{1}{k_3}$ etc., and for any circuit $R = \frac{1}{K}$, where R is the resistance and K the conductance.

The rule therefore for calculating the resistance of a circuit or part of a circuit made up of conductors in series, as indicated at (a) Fig. 10, is where R = total resistance

$$R = r_1 + r_2 + r_3 + r_4 + \text{etc.}$$

And for conductors in parallel, as at (b) Fig. 10, we have

$$\frac{1}{R} = K = k_1 + k_2 + k_3 + k_4 + \text{etc.}$$

$$= \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \frac{1}{r_4} \text{ etc.}$$

$$R = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \frac{1}{r_4} + \text{ etc.}}$$

This last expression is very cumbersome in ordinary work, and involves a somewhat tedious operation, except in the case of a number of conductors of equal resistance. In this case, if there be n conductors, it is clear that the denominator of the fraction on the right-hand side of the equation becomes $\frac{n}{r}$ so that as a result $R = \frac{r}{n}$; or, in other words, if you have n conductors of equal resistance in parallel, their joint resistance is $\frac{1}{n}$th the resistance of one. A glance at the expression for parallel resistances shows the fact, which may at first sight appear paradoxical, that if you put a resistance, no matter how high, in parallel with another, no matter how low, the effect is to produce a joint resistance less than the lower of the two

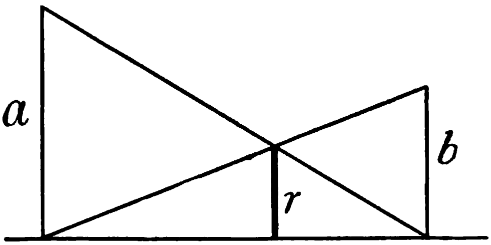


FIG. 11.—GRAPHIC CALCULATION OF JOINT RESISTANCE.

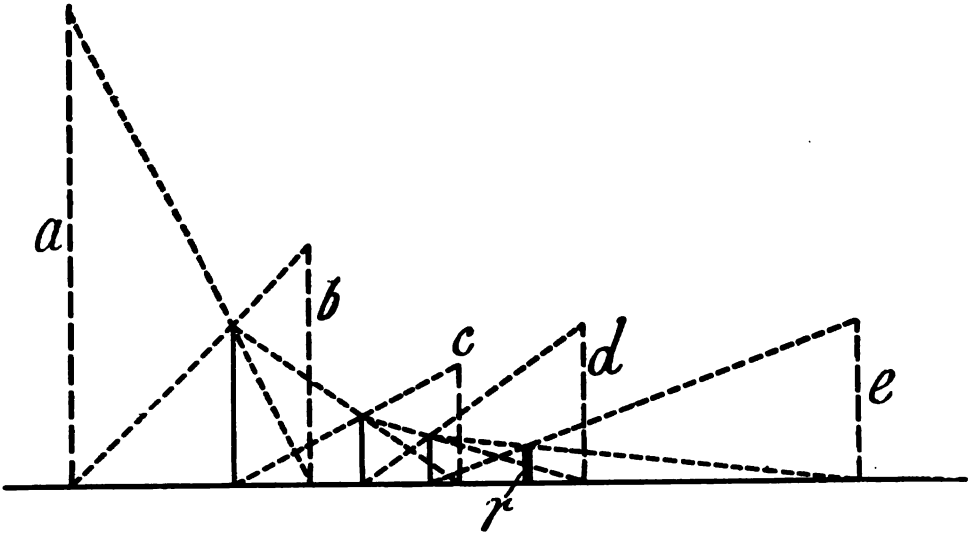


FIG. 12.—GRAPHIC METHOD OF CALCULATING RESISTANCE OF CONDUCTORS IN PARALLEL.

The calculation may be done graphically as follows, and the method may be instructive. Upon any base line set up a straight line *a* (Fig. 11) representing to scale the resistance of one of the parallel paths; at any convenient distance whatever from *a*, set up a line *b*, which must be parallel to *a*, representing to the same scale the resistance of the second parallel path. In the figure *a* and *b* are both drawn at right angles to the base line, but it is immaterial at what angle they be drawn with the base line, so long as they are parallel to one another, and on the same side of the base line. Now join the extremity of *b* with the base of *a*, and the extremity of *a* with the base of *b*. The height *r* of the point of intersection of these two lines last mentioned gives the joint resistance of *a* and *b* in parallel to the same scale as that adopted in setting off *a* and *b*. The greatest accuracy is attained when the two parallel lines are as far apart as possible. The diagram in Fig. 12 shows how this method may be applied to a number of conductors in parallel, the diagram having reference to five conductors *a*, *b*, *c*, *d* and *e*. It will be seen that a pair is first taken, and the joint resistance of this pair is found at the intersection of the two dotted lines, and then used to form a pair with one of the remaining resistances, and so on. Each joint resistance when found is drawn in by a full line, the last being a thick line and giving the joint resistance of the five conductors in parallel. Another graphic method is given in Fig. 13. In this case two parallel resistances are represented by the lengths of parallel lines *a* and *b*, on *opposite* sides of a base line. The distance chosen between *a* and *b* along the base line should

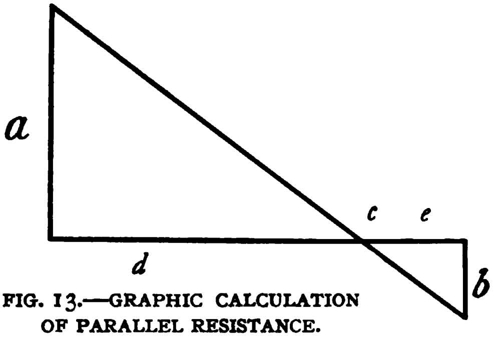


FIG. 13.—GRAPHIC CALCULATION OF PARALLEL RESISTANCE.

be some convenient length, say 10 cm The extremities of *a* and *b* are then joined by a line cutting the base at *c*, and dividing it into two portions, *d* and *e*. The joint resistance is now $\frac{d}{d+e} \times b$; or, what is the same thing, $\frac{e}{d+e} \times a$. For example, if $d+e$ is 10 cm. and *c* is 2½ cm. from *a* and 7½cm from *b* (*i.e.* $d = 2{\cdot}5$ and $e = 7{\cdot}5$), then the joint resistance of *a* and *b* in parallel is a quarter of *b*; or, what is the same thing, three-quarters of *a*. A reference to either of these graphical methods at once substantiates the statement just made, that putting a resistance, no matter how high, in parallel with another diminishes the total resistance, no matter how low that other.

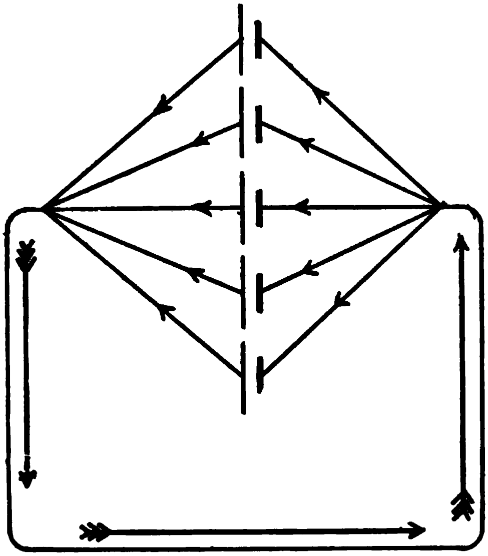


FIG. 14.—CELLS IN PARALLEL FEEDING A COMMON CIRCUIT.

CELLS IN PARALLEL AND SERIES.

Nothing of what has been hitherto said affords a solution to the question as to what will happen when cells are put in parallel to work on a common external circuit. The case may be very simply stated, so far as cells in series or cells of equal E.M.F. in parallel are concerned. If cells be connected in series, the total E.M.F. of the series is the sum of E.M.F.'s of the individual cells. This is true whether the individuals all help one another, that is to say tend to drive current in the same direction, or whether some are helping and some opposing. The algebraical sum must be taken, and the E.M.F.'s of cells acting in one direction must be regarded as positive, and those of the cells acting in the opposite direction as negative. The current will be regarded as positive or negative in its direction according as it flows with the E.M.F.'s that are regarded as positive or with those regarded as negative.

If cells of equal E.M.F. are placed in parallel with one another, the total E.M.F. at work is that of one cell only. This may be at first sight surprising, but a very common mechanical analogy will tend to make matters clear. A cell is a source of electric pressure, and cells in parallel feeding a common circuit are shown diagrammatically in Fig. 14. In this diagram the conventional symbol is used for a cell, the thick short line indicating the negative, and the long thin one the positive pole. The arrows indicate the direction of current. In a boiler-house it is common for a number of boilers, each of which is a source of pressure, to feed into one steam main, which supplies the engine-room. If each boiler generates a pressure of 120 lb. per square inch above atmospheric, the pressure in the steam main will only be, as everyone at once sees, 120 lb. per square inch above atmospheric. The function of the numerous boilers, which are really in parallel, is that of supplying steam at the rate necessary to meet the demand, for which a less number of boilers would be insufficient. So with our cells. If the electric pressure due to each cell be 1·5 volts, the total pressure in the circuit is only 1·5 volts, but the current passing to the external circuit is derived partly from each cell.

This matter is so commonly a source of difficulty to students, that it may be helpful to consider how boilers *may be imagined to be* placed in series so as to add their pressures. Before we discuss this, it is necessary to be very clear as to what is meant by a boiler pressure. A simple but accurate description of boiler pressure is that it is a tendency of the boiler to burst, or a tendency rather of every little unit area of the boiler shell to fly out at right angles to its own surface. If, therefore, we speak of a boiler pressure of 120 lb. per square inch, what we mean is that every little square inch tends to fly out with a force 120 lb. greater than the force with which it tends to fly in; that is quite apart from the holding together of the material itself. To put it still more clearly, a plate covering a hole in the boiler exactly an inch square would need an *added* 120 lb. from the outside to keep it on. It must not be supposed that boilers are ever placed "in series" in practice; the object of this description is merely explanatory. To place boilers in series, a boiler giving an internal pressure of 120 lb. per square inch above the atmosphere should be placed inside a larger boiler-shell. If now the space between the first boiler and this shell be used as a boiler and made to generate steam at a pressure of 120 lb. per square inch above the atmosphere, there will be no pressure tending to burst the inner boiler, the pressure just outside it being equal to that inside. In order, therefore, to produce the same stress tending to burst the inner boiler, we must raise the pressure in it to 240 lb. above the atmosphere. We now have two boilers in series, and if steam be taken through suitable piping from the inner boiler, we shall have a working pressure of 240 lb. per square inch. Another shell might similarly be placed outside this one, and so on, giving us a proportionate increase in pressure without any increase in the bursting stress of any one shell. Not only is this totally impracticable, but the analogue breaks down if we attempt to regard the steam as equivalent to the current, as is permissible for a single boiler. In the arrangement just described, on the contrary, no steam passes from the outermost space to the inside of the innermost boiler, as it would have to to be analogous to the electrical case, where current passes from one battery to another in series, and on passing through each acquires an added potential.

It will have been noticed that in speaking of boiler pressures reference was made to "atmospheric pressure" as a kind of standard, and the boiler pressure as being so much above atmosphere. The absolute pressure might have been given, taking a perfect vacuum as the standard or zero, and then the internal pressure would have been roughly 135 lb. per square inch, while the atmosphere would be given at 15 lb., making a difference, of course, of 120 lb.

POTENTIAL AND POTENTIAL DIFFERENCE.

In hydraulic work the level of the sea may be taken as a zero level, and the pressure obtainable from a water supply given in terms of the height if the supply be above the sea level. If the supply be down a mine, that is below the sea level, the pressure must obviously be regarded as negative. If a house be built on the sea level, and there be a tap on the ground floor communicating with a cistern at the top of the house, say 40 ft. above the ground floor, there is at the tap a pressure or head of 40 ft. If the whole house be now transplanted bodily to the top of Snowdon, say 3,000 ft. above sea level, a person using the tap will find no difference in the pressure with which the water comes out ; there will still be a *working* head of 40 ft. But we said just now that the sea level was to be considered our zero for measurements, and if the *cistern* be 3,040 ft. above the sea level, the head of water obtainable *at sea level* from the cistern is 3,040 ft. The head obtainable at sea level from the *tap* is, however, 3,000 ft., and we see that what the person in the house has to deal with is not the absolute pressure or head counted from sea level, but the difference between the level of the cistern and the level of the tap.

In electricity the "potential" of the earth is taken as zero, and this is equivalent, electrically, to calling the electrical pressure of the earth zero, just as we took the level of the sea to be zero.

The working pressure of a cell is in reality the difference between the potential of its positive pole above that of the earth and the potential of its negative pole above that of the earth, just as the working pressure in the house was the difference between the heights of the cistern and tap respectively above the sea. The actual potential of either the negative or positive pole is quite immaterial, just as the actual height of the house above the sea is immaterial. Now, when two points are put into conducting contact with one another, they become electrically one, and are at one and the same potential. If we have a number of cells of equal or unequal E.M.F.'s, they may be considered as equivalent to a number of houses of equal or unequal heights, each with its cistern at the top. The actual potential of either pole of any cell may be anything, and if no two cells be alike as regards the potential, say, of their positive poles, it will correspond to having our houses all at different altitudes. If we connect the positive pole of one cell with the negative of another, the potential of which is below it, we instantly bring that positive and that negative pole to one and the same potential, which is equivalent to the impossible feat of putting the tap in one house in communication with the cistern of another below it, and simultaneously moving either or both houses until the cistern of the second is exactly on a level with the tap of the first. In this case (the tap of the upper house being supposed to communicate by a watertight joint with the cistern of the lower house, and the cistern being supposed to be a closed one) the working pressure at the tap of the lower house is virtually the added height of the two houses, since that is now the difference in levels of cistern and tap. The total difference of potentials, similarly, between the negative pole of one cell and the positive pole of the next in series with it is the sum of the potential differences of the two. It is quite unnecessary to know the absolute potential of either pole above or below earth, it may be almost anything ; what is important is the potential *difference* between the poles.

FALL OF POTENTIAL.

If the difference of potentials at the terminals of a cell be measured by means of an instrument known as an electrometer, it will be found that as soon as current is taken from the cell this difference becomes less than it was when the cell was doing no work. When a cell is doing no work, that is when its poles are not connected to a complete circuit, it is said to be "on open circuit" ; and when the circuit is complete, so that a current can flow, it is said to be "on closed circuit." If the circuit between the positive and negative poles be one of excessively low resistance, it is said to be a "short circuit," and the cell is said to be "short circuited," or briefly "shorted." This term is only applicable to circuits whose resistance is really negligible in comparison with the internal resistance of the cell. It must be clear that the path afforded to the current by the materials contained in the cell possesses some resistance, since this is the property of all conductors. The resistance of the materials forming the path through the cell from the negative to the positive terminal is called, therefore, the "internal resistance" of the cell, or sometimes merely the "resistance of the battery." Now when the potential difference at the terminals is measured while the cell is doing no work, that potential difference is the full difference due to the contact between the materials employed (see below) in the cell, and is subject to no losses or deductions. This constitutes the E.M.F. of the cell. In fact, the term "E.M.F. of a cell" is precisely equivalent to the terminal difference of potentials on open circuit, and it is in this sense that the term will always be used in the following pages.

As soon as the cell begins to send current, some electromotive force is needed to drive the current through the internal resistance of the cell. The only source of electromotive force is the cell itself, and hence the potential difference at the terminals will now be less than on open circuit by an amount representing the E.M.F. absorbed in overcoming the internal resistance. In all cases where a current flows through a resistance, E.M.F., or potential, is absorbed, and energy is converted from an electrical form into heat. We have already seen that an E.M.F. is a difference of potential between two points, and it will therefore be clear that an absorption of E.M.F. is really a fall of potential. In a subsequent chapter it will be seen that the total E.M.F. of a cell is made up of two or more parts. In the case of the simple voltaic element a large difference of potentials is set up between the acid and the zinc by their mutual contact, the zinc being at the higher potential. The contact of the copper and the acid sets up a smaller difference acting in the opposite direction; that is to say, the copper is at a higher potential than the acid. There are thus two opposite differences, one greater than the other, and the total working difference is the algebraic sum; or, numerically, the difference of the two. At this point we are not concerned with more than this mere statement, and for our present purpose it is sufficient to regard the zinc-acid surface as the sole seat of a potential difference, and to consider it as being equal to the true value *less* the amount of opposing effect at the acid-copper surface.

In the light of this let us trace an element of current, *i.e.* a little charge round the circuit, considering its potential all the way along. Just at the zinc-acid contact surface it experiences by our hypothesis a sudden rise in potential. This we may liken to the water at the tap being suddenly carried up (by a pump, say) to the level of the cistern. The acid through which it must next pass has resistance, and the charge loses potential in traversing it. The potential falls by an amount depending on the resistance of the acid. So, too, in the copper; this has some resistance, and so has the external circuit, and the charge everywhere loses potential in proportion to the resistance it has to pass through, just as an automobile vehicle loses petrol in proportion to the resistance to motion. Finally, on arriving again at the zinc pole the charge has lost all its working potential with the exception of an amount just enough to carry it down the zinc to the surface of contact with acid, where a fresh supply is available.

We thus see that there is a steady and continual fall of potential all round the circuit. The question naturally arises, "How comes it that the supply of potential is always just exhausted when the current gets round to the zinc again?" The answer is given by Ohm's law. In Ohm's law the electro-motive force considered may be the whole of the electromotive force of the cell, or it may be only part, but whichever it is, the resistance and current considered must be those corresponding with the E.M.F. considered. In the present case it is the whole E.M.F. of the cell that we are considering, for the current starts (so to speak) with it all, and loses it all in the circuit. In other words, the *whole* E.M.F. is absorbed in the *whole* circuit. Now, Ohm's law is:

$$E = C\,R \text{ or } C = E/R,$$

from which we see that, on the one hand, the E.M.F. absorbed is proportional to the *current* as well as to the resistance, and on the other that, with a given E.M.F., the current is inversely proportional to the resistance. Hence, in a circuit of given E.M.F. and resistance, the current which flows will always be of *just* such a value as *just* to absorb all the E.M.F. In fact, it automatically adjusts itself to that value, and must do so, as is clear from the equation.

It is also clear, from what has here been said, that the potential is continually changing from point to point of the circuit, and hence no two points are at the same potential *when a current is flowing*. In other words, there is a difference of potentials between any two points in a conductor carrying a current. This potential difference (P.D. is the commonly used abbreviation) is the E.M.F. used to drive the current from the one point to the other, and is known either as the "fall of potential" or as the "voltage drop" between the points. It is also known as the P.D., or potential difference, but care is necessary in the use of this term, since it is also applied to a cell or other generator. A mere conductor is an absorber of electrical energy, while a cell is both absorber and generator, usually (except on short circuit) more of a generator than an absorber. Hence what is known as the P.D. of a cell, or the P.D. at the terminals *of a cell*, does not mean the voltage drop due to its resistance, as in the case of a mere conductor, but means the *E.M.F. of the cell less that drop*. Of course, if these, that is the E.M.F. and the drop, are equal, as is the case on short circuit, the P.D. is 0; on the other hand, when there is no current, there is no drop, and the P.D., as was shown above, is equal to the E.M.F. In the case of a mere absorber of electrical energy, the P.D. and the voltage drop mean, and are, the same thing. It must be carefully noted that what is here meant by a "mere absorber" is a conductor possessing resistance only, and not some device with an active E.M.F. in it. The resistance absorbs the energy by converting it into heat. This heat is ordinarily lost in a wasteful way, and the fact of the energy being lost in a heat form is neither here nor there. Where E.M.F.'s are at work as well as resistance, we shall see that, if they oppose the flow of current, energy is transformed to some form other than heat as a rule, and, moreover, generally to some useful form.

APPLICATION OF OHM'S LAW.

To fix our ideas it will be well to take a few cases and deal with them numerically.

A cell having an E.M.F. of 1·5 volts, and an internal resistance of 0·25 ohm, is driving current through a wire joining its terminals. The resistance of the wire is half an ohm.

Here the total E.M.F. in the circuit is 1·5 volts, and the total resistance is the sum of 0·25 and 0·5 = 0·75. Hence, since

$$C = \frac{E}{R},$$

$$C = \frac{1{\cdot}5 \text{ volts}}{0{\cdot}75 \text{ ohms}} = 2 \text{ amperes.}$$

As regards the voltage at the terminals of the cell (or the P.D. of the cell), it will be 1·5 volts minus the loss due to internal resistance. In this case the loss is by Ohm's law

$$e = c \times r$$

$$\text{or } e = 2 \text{ amps.} \times 0{\cdot}25 \text{ ohm}$$

$$= 0{\cdot}5 \text{ volt.}$$

Thus half a volt is expended, *with this current*, in overcoming the internal resistance, and the terminal voltage is one volt. This one volt is then at our disposal for sending current through the external resistance, and, if our first calculation was correct, we shall find that this is just the necessary voltage to get the current through this resistance. Applying the law to find what voltage is wanted, we see that this must be equivalent to the fall of potential due to *that* current down *that* resistance, and so

$$\text{voltage wanted} = 2 \text{ amps.} \times \tfrac{1}{2} \text{ ohm}$$

$$= 1 \text{ volt,}$$

which agrees.

Now, suppose the wire in question to be a long stretched wire of uniform cross section, its length being 20 feet. Since it is of uniform size and material, the resistance of any one inch length will be just the same as that of any other inch length; and, since the same current flows through the whole length, it follows that the voltage drop down any one inch is equal to that down any other. We can at once find what it is numerically. The resistance of the whole length is ½ ohm, and the length is 20 feet, or 240 inches, so that the resistance of one inch is $\frac{1}{480}$th of an ohm. The voltage drop, or fall of potential down an inch, is given by the resistance multiplied by the current as before; in this case it is

$$2 \text{ amperes} \times \frac{1}{480} \text{ ohm} = \frac{1}{240} \text{ volt.}$$

We thus see that by taking two points on the wire the right number of inches apart we can get two points at any required difference of potentials less than one volt: *any* two points ten inches apart will give $\frac{1}{24}$th of a volt. We need not take an exact number of inches, of course, and can get, for instance, a P.D. of 0·3 volt by taking points 72 inches apart. This fact is made great use of in practice, and enables small variations in voltage to be obtained. A device embodying this idea is called a "potentiometer."

Next let us consider the effect of varying the external resistance. We will increase it first to 0·75 ohm, and then reduce it to 0·25 ohm, and finally to so low a value as to be negligible.

If the external resistance be 0·75 ohm the current will be equal to

$$\frac{1{\cdot}5 \text{ volts}}{(0{\cdot}25 + 0{\cdot}75) \text{ ohms}} = 1{\cdot}5 \text{ amperes;}$$

the terminal voltage of the cell can be calculated in two ways as before, either thus—
1·5 volts less (1·5 amps × 0·25 ohm), *i.e.*
1·5-0·375 = 1·125 volts,
or thus—
volts required on external circuit are 1·5 amps. × 0·75 ohm = 1·125 volts.

If the external resistance be 0·25 ohms, the current is

$$C = \frac{1{\cdot}5 \text{ volts}}{0{\cdot}25 \times 0{\cdot}25 \text{ ohms}} = 3 \text{ amperes,}$$

and the terminal voltage is 0·75 volt, for the fall due to 3 amps. through 0·25 ohms is 3 × 0·25 = 0·75 volts.

If the external circuit is of a very short, very thick piece of copper, its resistance is negligible, and the only resistance is that of the cell, hence

$$C = \frac{1{\cdot}5}{0{\cdot}25 + 0} = 6 \text{ amperes,}$$

and the terminal voltage is 0; that is to say, all the voltage is used up in getting the current through the cell, and none is needed or used in the external resistance because it is zero. Strictly speaking, "none" here means a quantity so small as not to be measurable.

These examples show the variation in the voltage consumed by the internal resistance of the cell. In all cases it is proportional to the current, and hence depends on the external resistance. It was 0·475, 0·5, 1·25, and 1·5 when the external resistance was 0·75, 0·5, 0·25, and 0 respectively.

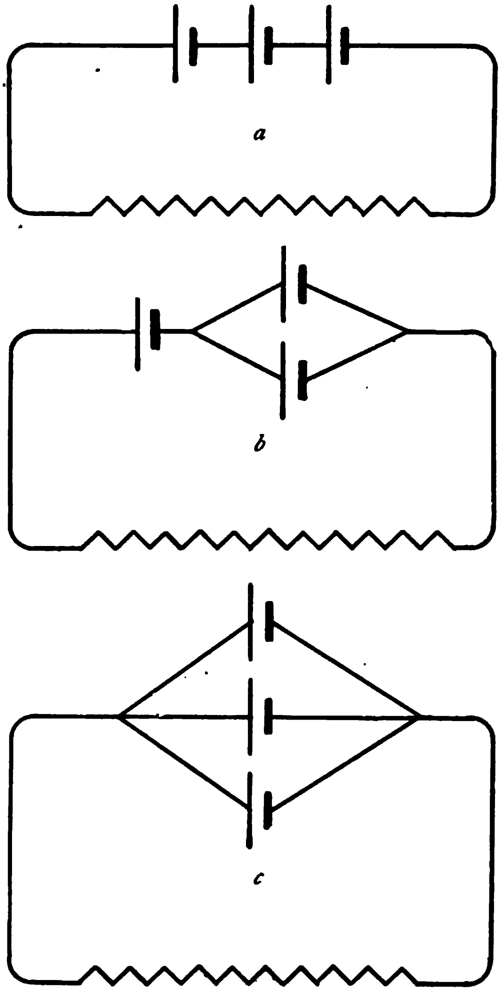


FIG. 15.—CELLS IN SERIES, IN PARALLEL AND TWO IN PARALLEL IN SERIES WITH THE THIRD.

Now consider a battery of several cells at work on a less simple circuit.

If we have, say, three cells all alike, we can arrange them either all in series, or all in parallel, or two in parallel in series with the third. These three arrangements are represented at *a*, *c*, and *b* respectively (Fig. 15). It is not, however, either usual or advisable to adopt an unsymmetrical arrangement of cells that are alike, except for very special purposes, hence the arrangement at *b* is rare. In case *a* the total E.M.F. at our disposal is three times that of one cell, and the internal resistance of the combination is three times that of one cell. In case *c* the E.M.F. available is that of one cell only, and the internal resistance of the arrangement is one-third that of one cell (see page 24). In case *b* we have the E.M.F. of two cells, and an internal resistance equal to $\rho + \frac{1}{2}\rho = 1\frac{1}{2}\rho$, where ρ is the internal resistance of one cell. As a rule, two cells in series would be used to give the required voltage of twice that of one cell, but the internal resistance would also be twice that of the cell, and hence the advantage of the third cell, added to the other two as at *b*, is that it reduces the resistance from 2ρ to $1\frac{1}{2}\rho$ without reducing the E.M.F.

Again a few figures will fix our ideas. Let the cells be similar in composition and size to the one mentioned above. Let us put the cells to work on the same external resistances as before, and try the three arrangements. The results are given in the following tables :—

Arrangement.	*a*	*b*	*c*
E.M.F. ...	4·5	3	1·5
Resistance of battery ...	0·75	0·375	0·083

In the second table, *r* is the external and R the total resistance ; the last column gives the ratio between r_1 the internal resistance of the battery of cells and the total resistance of the circuit. This ratio is also the ratio of the wasteful to total energy in the circuit, and the figures given show

External resistance r	Total Resistance. R (Ohms).			Current. (amperes).			Terminal Volts.			$r/_{1}R$ %		
	a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
0·75	1·5	1·125	0·833	3	2·66	1·8	2·25	1·99	1·35	50	33	10
0·5	1·25	0·875	0·583	3·6	3·425	2·575	1·8	1·71	1·28	60	42·8	14·2
0·25	1·0	0·625	0·333	4·5	4·8	4·5	1·125	1·2	1·125	75	60	24·8
0·0	0·77	0·375	0·083	6·0	8·0	18·0	0	0	0	100	100	100

the percentage waste. It is at once noticeable that the percentage waste increases as the external resistance decreases.

As an indication of the way in which more complicated circuits are to be dealt with, we will consider the circuit shown diagrammatically in Fig. 16. We have there twelve cells forming the battery arranged "3 in parallel, 4 in series," and these are together at work on an external circuit made up of six wires. These are arranged in a somewhat complicated way, and our first business must be to determine what resistance they offer. As usual, the resistances of the connecting wires (shown straight) are regarded as negligible in comparison with the resistances of the wires (shown curled) whose resistances are marked against them.

In all cases such as this we must begin by taking each group of simple parallel wires and evaluating the resistance of that group. This being done, the group may be supposed to be replaced by a single wire of the calculated resistance, and we again simplify by reducing parallel groups to one wire, resistances in series being added.

Here we see at once two groups, one of three, and one of two wires in parallel, which must be reduced. The first group is equivalent (*see* page 24) to a resistance of $\frac{1}{\frac{1}{2}+\frac{1}{3}+\frac{1}{6}}$ ohm, which works out to 1 ohm.

The second is $\frac{1}{\frac{1}{30}+\frac{1}{6}}$ ohms, that is 5 ohms.

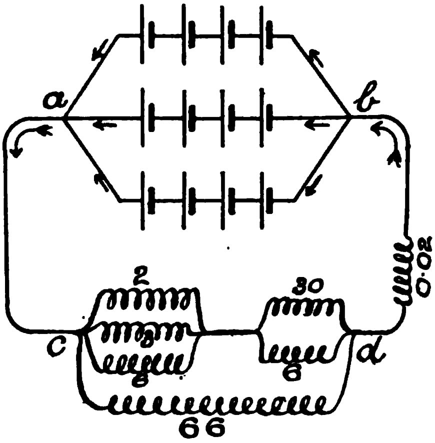


FIG. 16.—CALCULATION OF COMPLEX CIRCUIT.

These two groups may therefore be replaced by two wires of 1 ohm and 5 ohms respectively, or, since they are simply in series, by one wire of 6 ohms. This one of 6 ohms is then in parallel with one of 66 ohms, giving a joint resistance of 5·5 ohms. Thus we have cleared away, so to speak, all the complex part of the circuit by successive simplifications, and have only to add in the 0·02, giving 5·52 for the total *external* resistance. Now to apply Ohm's law we must get the figures for the entire circuit. We need, therefore, the internal resistance of the battery. Suppose each cell to have an internal resistance of 0·36 ohm. Each row of 4 cells will have 1·44 ohms resistance, and as there are 3 rows in parallel the 12 cells will give (see page 24)

$\frac{1}{3}$ of this, or 0·48 ohms. This, with the external resistance of 5·52 ohms, gives a total in the circuit of 6 ohms.

Next, if the E.M.F. of each cell is 1·8 volts, that of a row of 4 will be 7·2 volts, and that is the total E.M.F. at work (p. 26). We can now apply Ohm's law to the whole circuit. Total resistance is 6 ohms, total E.M.F. 7·2 volts, hence

$$\text{current} = \frac{7{\cdot}2}{6} = 1{\cdot}2 \text{ amperes.}$$

This is the current *leaving the battery*, and as the battery is composed of three precisely similar parallel rows, each row contributes one-third, or 0·4 amperes.

So much for the circuit as a whole; let us now analyse it by the application of Ohm's law to the several parts. All that is needed is (see p. 23) care that the figures employed shall relate to precisely the same parts.

Firstly, it was stated just above that the current divides itself equally between the three similar portions of the battery. We can prove this and recalculate the current through each cell.

The total voltage is 7·2, the total internal resistance 0·48, and the total current 1·2; multiplying these last two together we get 0·576 as the voltage absorbed in getting the total current through the whole battery, and deducting this from 7·2 we have 6·624 as the terminal voltage. Now, the terminal voltage is the difference of potentials between the two points *a* and *b*, Fig. 16, and is therefore the same for each of the three rows. Hence each of the three rows loses 0·576 volts, owing to its internal resistance, which we have seen is four times 0·36, *i.e.* 1·44 ohms. These figures are the same for each row, and applying Ohm's law to get the current which will cause this loss of voltage we have

$$C = \frac{{\cdot}576}{1{\cdot}44} = 0{\cdot}4 \text{ ampere.}$$

Next, consider the distribution of current in the various parts of the external circuit. The grouped wires had a resistance of 5·5 ohms and carry the whole current, hence the voltage absorbed in this part of the circuit is 6·6. Note, this is the voltage between the points *c* and *d*, and hence applies both to the 66 ohm path and to the path of grouped wires above it. Consider the 66 ohm path, applying Ohm's law:

$$C = \frac{6{\cdot}6}{66} = 0{\cdot}1 \text{ ampere;}$$

that is, this branch carries 0·1 ampere, leaving 1·1 amperes to flow by the other path. Just to check this we find for the upper path of 6 ohms that 6 ohms × 1·1 ampere require 6·6 volts to drive the current, which is, of course, what we have.

In a precisely similar way we can deal with the two groups of the upper path; the current entering any group of parallel wires being divided between them in inverse proportion to their respective resistances. Hence the 2 ohm branch will carry 0·55 amperes, the 3 ohm branch 0·367 amperes, and the 6 ohm branch 0·183 amperes.

Emerging from the grouped wires, the current traverses the 0·02 ohm resistance, absorbing a further 0·24 volt, thus making up the total of 6·624 volts.

SECTION II.

PRIMARY AND SECONDARY CELLS.

CHAPTER I.—THE VOLTAIC CELL.

THE CELL AS A FURNACE—THE VOLTAIC CELL—CONSUMPTION OF FUEL—CHEMICAL ACTIONS IN A CELL—THE ALIMENT—LOCAL ACTION—POLARISATION—E.M.F. AND RESISTANCE OF CELLS—CARBON RESISTANCE FRAME—QUALIFICATIONS OF A GOOD BATTERY.

THE CELL AS A FURNACE.

THE existence of an electric current in any circuit means that energy in some form is being liberated at the generating source; and the continuance of this current necessitates the continuous expenditure of energy. In the case where the current is supplied by a dynamo driven by a steam or gas engine, the source of the supply is the coal, and the place where the energy is being liberated is the furnace. Coal, in its relation to air, contains a large supply of energy, which it readily liberates in a furnace in the form of heat, and which, after undergoing several transformations, appears in the circuit in the form of a current, and is there utilised for lighting, electro-deposition, or some such purpose. The coal becomes oxidised or burnt up in the process, and the quantity of energy that can be thus obtained is clearly limited by the amount of coal consumed. The series of transformations is by no means an economical one, and considerable improvement may yet be looked for in this direction.

In the case of an ordinary voltaic cell the conversion of the energy of supply into energy in the form of the electric current is a much simpler and more economical process, but the material which acts as the source of supply—in other words the fuel—is far more expensive. In most cells the fuel consists of zinc, which is oxidised or burnt up, but which, instead of giving out its energy in the form of heat, gives it out directly in the form of current. A cell is in reality nothing more than a little furnace in which zinc instead of coal is used as fuel and in which the "burning" is not simple oxidation. Zinc can be burnt in an ordinary furnace if proper precautions are taken, and a certain quantity of it will give out a perfectly definite amount of heat which will, however, depend upon the thoroughness of the burning. If "burnt" in a cell it will give out a perfectly definite quantity of electricity at a voltage which depends on the kind (*i.e.* degree) of "burning" effected. The quantity of electricity multiplied by voltage represents the amount of energy given out. The amount of energy that we can obtain by the consumption of a given quantity of zinc, or of any other material, depends upon the goodness or badness of that material as a fuel. Certain of the metals are the materials best adapted for the fuels in cells, and the relative amounts of energy that can be obtained from any one of them are similar to the relative amounts of heat that could be obtained from them if burnt in a furnace. The *heat value* of the material is, therefore, the guide that must be looked to when selecting a material for a cell. The following list contains the amount of heat, in calories, given off in uniting with oxygen by a weight of each substance which is electro-chemically equivalent to one gramme of hydrogen.

TABLE I.—HEAT VALUES OF SUBSTANCES.

SUBSTANCE.	HEAT VALUE IN CALORIES.
Potassium	69·800
Sodium	67·800
Zinc	42·700
Iron	34·120
Hydrogen	34·000
Lead	25·100
Copper	18·760
Silver	9·000
Platinum	7·500
Carbon	2·000
Oxygen	0
Nitric acid	— 6·000
Black oxide of manganese	6·500
Peroxide of lead	12·150
Permanganic acid	— 25·070

A calorie is the amount of heat required to raise the temperature of 1 gramme of water from 0° to 1° Centigrade.

Potassium and sodium are evidently the materials that from a theoretical standpoint should be used as the fuels in cells, but, unfortunately, practical considerations forbid their use. In the first place they are far too expensive, and in the second place their tendency to unite with any oxidising liquid is so great that heat is given off sufficiently quickly to make the material take fire. Zinc is the material that comes next on the list, and as there are no practical objections to its use we find that it is the material most widely used. It gives out more heat on burning than its equivalent of coal. The ordinary primary battery, when suitable arrangements are made, will continue to generate current with more or less vigour till all the fuel is consumed, or until the oxidising agent is exhausted, fresh supplies should then be provided, or the cell will become inactive.

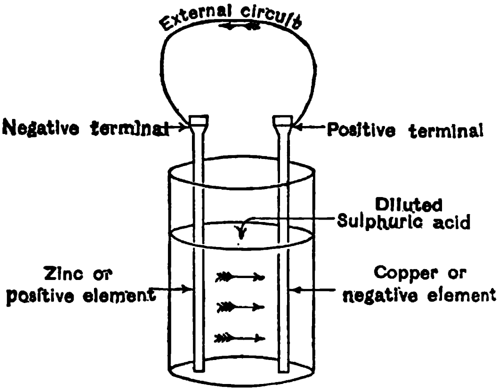


FIG. 17.—SIMPLE ELECTRIC CIRCUIT.

THE VOLTAIC CELL.

If a rod of absolutely pure homogeneous zinc be immersed in a vessel (Fig. 17) containing dilute sulphuric acid, we might expect, as one is a good fuel and the other a highly oxidising liquid, that chemical action would at once start and continue till all the zinc was consumed; but if we perform the experiment we shall find that no such action occurs. The zinc remains unacted upon however long it is allowed to remain in the liquid. If a copper rod be now placed in the liquid, but without touching the zinc, the condition of affairs will not be changed. Both materials remain perfectly quiescent, and though both are fairly good fuels, neither heat nor current is generated. If the two metals are now made to touch outside the liquid, or if they are connected by a wire or anything capable of carrying a current, this state of inaction is immediately changed. A current at once starts and flows across the liquid from the zinc to the copper, up the copper rod to the terminal, through the wire connecting the two metals, and so back to the place from which it started. This course is indicated by the arrow heads in Fig. 17. The two metals, as soon as the external circuit is completed by the wire, tend to oxidise and to drive currents from themselves through the completed circuit; but, as it is clear that two currents cannot flow in opposite directions through the same circuit at the same time, these currents cannot both flow. If the two materials have the same heat values, they tend to drive currents through the circuit with equal forces, and consequently no current can flow; but if one has a higher heat value than the other, it will have a greater force tending to drive a current, with the result that a current will flow through the circuit starting at the surface of the metal which has the higher heat value. The force driving this current is called the electromotive force of the cell, and is proportional to the difference between the heat values of the two metals. On reference to the table (1) it will be seen that zinc has a heat value of 42·700, whereas copper has only 18·760; the current will therefore start at the surface of the zinc and flow through the circuit in opposition to the force between the copper and sulphuric acid.

During the whole of the time that the current is flowing the zinc is being consumed, whilst the copper remains unacted upon. The zinc, therefore, is the material which acts as the fuel in the cell, and for this reason it is known as the POSITIVE ELEMENT, and the copper is known as the NEGATIVE ELEMENT. In every cell the substance which has the higher heat value, and which consequently acts as the fuel, is the positive element.

The terms positive and negative poles must not be confused with positive and negative elements. The *positive pole* is that part where the current leaves the cell and enters the external circuit—it is clearly the upper part or terminal of the negative element. Similarly, the *negative pole* is the upper part or terminal of the positive element.

CONSUMPTION OF FUEL.

The quantity of material that is consumed in a cell for delivering a certain quantity of electricity, that is, for the maintenance of a certain current for a given time, depends upon the electrochemical equivalent of the material con-

TABLE II.—ELECTRO-CHEMICAL EQUIVALENTS.

MATERIAL.	ELECTRO-CHEMICAL EQUIVALENT (GRAMMES).	ATOMIC WEIGHT.	VALENCY.
Hydrogen	0·00001034	1	1
Oxygen	0·00008286	15·96	2
Chlorine	0·0003673	35·37	1
Nitrogen	0·00004849	14·01	3
Potassium	0·0004539	39·03	1
Sodium	0·0002387	23·00	1
Silver	0·001118	107·67	1
Copper (cupric)	0·0003271	63·18	2
Mercury (mercuric)	0·0010374	199·8	2
Tin (stannic)	0·0003058	117·8	4
Iron (ferrous)	0·0002902	55·9	2
Zinc	0·00033696	64·9	2
Lead	0·0010716	206·4	2

sumed, and provided we know this factor we can calculate the exact consumption. The table on the previous page contains the electro-chemical equivalents of a number of materials; that is to say, the quantity of the material deposited from a solution by the passage through it of one coulomb (one ampere for one second).

Example.—What will be the consumption of zinc in a cell which gives an average current of two amperes for a period of three hours?

The amount consumed in one second is clearly

$$2 \times 0{\cdot}00033698 \text{ grammes,}$$

and this quantity must be multiplied by the time in seconds thus—

$$\begin{aligned}\text{Weight} &= 2 \times 0{\cdot}00033698 \times 3 \times 60 \times 60 \\ &= 7{\cdot}279 \text{ grammes.}\end{aligned}$$

This is the quantity of pure zinc that would be necessary to maintain the current, provided there were no losses and that all the energy in the zinc took the form of useful current. In practice this is found not to be the case, for reasons that will be afterwards explained, and in fact a larger quantity is always used.

CHEMICAL ACTIONS IN A CELL.

Both pure water, pure sulphuric acid, and all other pure liquids, are to be regarded as practically non-conductors. Directly a solution is made, however, as when sulphuric acid and water are mixed, the sulphuric acid is in some degree dissociated by the water into positive and negative ions. At the surface of both the electrodes there is also dissociation by the water, and on open circuit there is an interchange of ions between each electrode and the electrolyte, until a condition of equilibrium is reached, in which both electrodes have attained higher potentials than that of the electrolyte. This rise of potential is due to the neutralisation and discharge of the ions, and is of course not the same at the two electrodes, the difference constituting the E.M.F. of the cell. The dissociation of a substance in solution gives rise to what is called osmotic pressure, a definite mechanical force within the liquid, and if this force is greater than that with which the metallic ions of the electrode tend to enter the liquid (solution pressure), ions from the electrolyte penetrate the surface of the electrode and combine with metallic ions. If the solution pressure is greater, the reverse occurs and metallic ions enter the solution, displacing ions with less affinity for water. These interchanges must clearly continue until the pressures are equalised and a state of equilibrium is reached. If this state of equilibrium is disturbed by closing the external circuit the interchanges are at once free to continue and do so throughout the electrolyte also, so that positively charged hydrogen ions are liberated at the copper, and the zinc ions at the other end combine with the SO_4 ions. The reaction may be expressed thus—

$$Zn + H_2SO_4 = ZnSO_4 + H_2.$$

The sulphuric acid in the cell is thus gradually converted into sulphate of zinc, which is comparatively heavy and sinks to the bottom of the cell; the zinc gets gradually consumed, the solution gets weaker, and the copper gets covered with hydrogen. This last effect plays an important part in the working of the cell, as we shall see when dealing with "polarisation."

THE ALIMENT.

From a brief consideration of the chemical actions in a cell we see at once that the quantity of zinc is not the only factor that determines the length of time that the cell is capable of generating current. The current will continue to flow till either the zinc or the oxidising agent with which it is uniting gets exhausted. When either of these things happens the current ceases. Contrasting this condition of affairs with that of an ordinary coal furnace, we find that the furnace burns so long as it is supplied with fuel in the shape of coal, and an oxidising agent in the shape of the oxygen of the air. Under ordinary conditions the supply of air is unlimited, and the supply of fuel is the only thing we have to look to, but if the supply of air be cut off the fire will quickly die out. The air is as necessary to the combustion of the coal as the sulphuric acid is to zinc —a failure in the supply of either immediately terminates the combustion. In a cell, the oxidising agent is called the *aliment.*

The action of the fire as well as of the cell clearly depends on the nature of the aliment. If ozone were substituted for air, the energy of combustion would be much increased. Similarly, in the case of the cell, the action might be increased by substituting for sulphuric acid some more strongly oxidising agent, such as bichromate or permanganate of potash. In the cell, unlike the furnace, the amount of aliment is limited, so that it may fail to work either through failure of the supply of fuel or of aliment.

LOCAL ACTION.

It has been explained why a piece of pure zinc is not attacked when immersed in dilute sulphuric acid—there is no path along which the current that starts from its surface can return there, but in the case of ordinary commercial zinc the condition of affairs is completely changed. This zinc contains many impurities, the principal of which are iron, arsenic, and small pieces of coke, and these small impurities on the surface of the zinc, and in contact with the acid, supply the necessary paths for the return of the currents that start from the zinc. In the vicinity of each of these little foreign bodies the zinc enters into combination with the acid, currents start outward through the liquid and return to the zinc through the foreign bodies. These little eddy currents continue to flow wherever an impurity exists on the surface, and result in bubbles of hydrogen being given off and rising through the liquid. By this means the existence of *local action* can always be recognised. When local action once starts it becomes a continually increasing quantity; as the zinc is being dissolved fresh impurities are being exposed, which immediately start local eddy currents of their own as soon as they come in contact with the acid. Unless means are adopted to prevent the local action, the whole of the zinc will be quickly consumed, and the energy which was stored up in it take the form of current, which in its turn will expend itself in heating the cell. It is almost impossible to obtain zinc which will not show local action—even the inequalities in structure of pure zinc itself will be sufficient to start it.

There is one plan by which local action can be prevented even when common commercial zinc is used as the fuel, and that is by covering its surface with an amalgam* of mercury. The process of amalgamation is simple: if the zinc is very greasy, it should be boiled in a solution of caustic soda, and then dipped in dilute sulphuric acid, but usually the dipping in sulphuric acid is sufficient. It is then dipped in mercury, when its whole surface shows a bright metallic lustre. If any spots remain which are not covered with mercury, it may be again dipped in the sulphuric acid and rubbed over with a piece of tow or cork. The result will be that the whole of the surface will be covered with an amalgam of zinc and mercury, and all the impurities will be covered with this amalgam. It will now behave as if it were absolutely pure zinc, and local action will be entirely checked. The mercury does not appreciably interfere with the properties of zinc as a fuel, and its electromotive force remains practically unchanged. As the zinc in the amalgam gets consumed, the mercury remains behind and unites with each fresh portion of zinc as it becomes exposed, thus preserving a thoroughly amalgamated surface till the whole of the zinc has been consumed. Instead of amalgamating the common zincs, a better plan is to mix about 4 per cent. of mercury with the zinc in the process of casting.

---

* An amalgam is virtually a solution of a metal in mercury.

POLARISATION.

When the sulphuric acid is decomposed in the ordinary working of the cell, the free hydrogen first settles on the copper plate, forming a layer over the whole of its surface, and any further hydrogen that is given off simply rises through the liquid. The copper plate now behaves exactly as if it were made of hydrogen, and when in this condition the cell is said to be *polarised.*

The electromotive force of a cell depends upon the difference between the heat values of its elements, and a reference to Table 1 will at once show that the electromotive force of the cell must be considerably reduced when polarised. The difference between the heat values of zinc and copper is 23·940, and between zinc and hydrogen 8·700, so that we would expect the E.M.F. (electromotive force) to fall to about one-third of its original value. This is what we actually find in practice. The E.M.F. at starting is about 1 volt, which immediately begins to decrease as soon as the cell gives out current, and falls to about one-third of a volt as soon as the copper plate has become thoroughly covered with hydrogen. This leads at once to the conclusion that the material composing the negative element has no effect whatever on the E.M.F. of the cell when once polarised, provided it has a lower heat value than hydrogen. No matter what material we start with, it quickly gets covered with the film of hydrogen, and from that time onward zinc and hydrogen are really the positive and negative elements of the cell. Platinum or carbon having lower heat values than copper would give higher E.M.F.'s in combination with zinc, but this very desirable gain would only be momentary ; as soon as the hydrogen layer was once formed the E.M.F. would drop to about one-third of a volt. Besides lowering the E.M.F. the hydrogen plays another important part in the working of a cell, and one which is almost as objectionable. It is an extremely bad conductor, and when once the film of gas is formed over the negative element a comparatively high resistance is introduced into the path which the current has to traverse. This twofold effect of the free hydrogen makes it desirable to prevent its formation if possible, or to get rid of it when formed with all speed.

A single cell may not always be able to send a sufficiently strong current through a given external resistance, though a group of cells may. Such a group of cells is called a battery, and Fig. 18 shows the manner in which they should be connected up. The zinc of cell No. 1 marked — forms the negative pole of the battery ; the copper of this cell C is joined to the zinc Z of No. 2, the copper C of No. 2 to the zinc Z of No. 3, and so on, the copper terminal of the last cell marked + forming the positive pole of the battery. The E.M.F. of this battery of five cells is five times as great as the E.M.F. of a single cell, but the resistance of the battery is also increased in the same ratio. The arrows show the direction of the current through the cells when the external circuit is completed, so that exactly the same strength of current

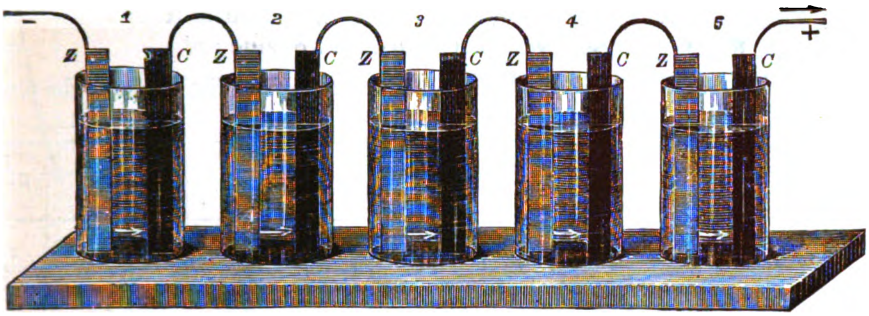


FIG. 18.—CELLS CONNECTED IN SERIES.

passes through each cell, no matter how much they may differ either in E.M.F. or resistance. From this it follows that when the cells are grouped in *series* as shown, the same amount of zinc is consumed in each cell. To know, therefore, the total amount of zinc consumed in such a battery it is only necessary to find the amount consumed in a single cell, as shown in Example 1, and multiply by the number of cells in series.

E.M.F. AND RESISTANCE OF CELLS.

The E.M.F. of a cell depends entirely upon the chemical properties of its constituents, and is independent of the size, shape, or arrangement of those materials. The heat values of the materials determine the E.M.F., and a knowledge of these values will enable us to predetermine approximately the E.M.F. of any combination. Of course when polarisation starts the E.M.F. begins to drop, and continues to do so till the whole of the negative element has been covered, when the E.M.F. attains a fixed value, which remains quite constant however long the cell is required to give current; but it must be remembered that during this operation the negative element really undergoes a change from its original nature to that of hydrogen. We can predetermine the E.M.F. of the combination at starting, and also when the steady stage of polarisation is reached, and between these two values the E.M.F. undergoes a continuous change, depending upon the amount of uncovered surface of the negative element.

The resistance of a cell depends upon: (*a*) The conducting powers of the elements, but this is usually so great as to have an inappreciable effect; (*b*) the conductivity of the aliment, which is usually an important factor; (*c*) the size of the elements; (*d*) the distance between the elements; (*e*) the general arrangement of the constituents of the cell. When polarisation takes place, the film of hydrogen must also be taken into consideration. In ordinary simple cells the resistance of the elements themselves can be neglected, and the aliment forms practically the whole of the resistance. In this case the resistance of the cell depends directly upon the areas of the elements, and inversely upon the distance between them. Thus doubling the size of the plates or halving the distance between them will halve the resistance of the cell.

The resistance of a cell—when everything else is maintained constant—appears to depend in some way upon the strength of the current that is flowing. The greater the strength of current taken from the cell the smaller does its resistance appear to become. In order to determine the amount of this variation a series of experiments were carried out with the connections shown in Fig. 19 upon a circular Daniell cell, whose dimensions are shown in Fig. 20. The total E.M.F. of the cell was first measured on the voltmeter, the external circuit was then closed, and readings on the voltmeter and amperemeter taken simultaneously, whilst the current was varied by changing the resistance. The resistance of the cell was calculated from the expression

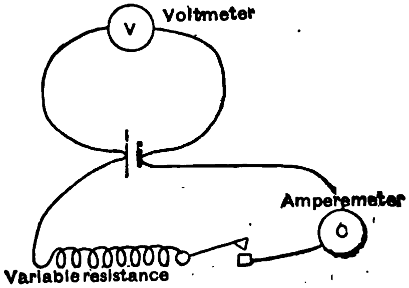


FIG. 19.—MEASUREMENT OF INTERNAL RESISTANCE.

$$B = \frac{E - V}{C},$$

where B = resistance of cell,
" E = total E.M.F. of cell,
" V = terminal " "
" C = current " "

Fig. 20 shows a plan of the cell upon which the tests were carried out. The outer vessel o consisted of a glazed earthenware pot, containing sulphate of copper ($CuSO_4$). In this was immersed a copper sheet c, bent so as to form about three-fourths of a cylinder. In this was placed the porous pot (p), which held the sulphuric acid (H_2SO_4) and the amalgamated zinc rod (z).

The following are the dimensions :—

Internal diameter of containing vessel = $3\frac{7}{8}''$
" " " porous pot = $2\frac{1}{2}''$
Thickness of porous pot = $\frac{1}{4}''$
Periphery of copper cylinder = $9\frac{1}{2}''$
Height of acid in cell = $4\frac{3}{4}''$
" " sulphate of copper = $3\frac{3}{4}''$
Density of copper sulphate = 1·170
" " sulphuric acid = 1·118
Diameter of zinc rod = $1\frac{1}{4}''$

The following list contains the results of the tests :—

E.	V.	C.	$B = \frac{E-V}{C}$.
1·07	·970	·100	1·00
1·07	·938	·15	·88
1·07	·910	·20	·80
1·07	·885	·25	·741
1·07	·865	·30	·683
1·065	·800	·415	·614
1·065	·770	·50	·590
1·065	·723	·60	·570
1·065	·633	·80	·540
1·07	·58	·90	·544
1·07	·54	1·00	·533
1·065	·49	1·10	·522
1·07	·46	1·20	·508
1·07	·42	1·30	·500
1·07	·395	1·40	·482

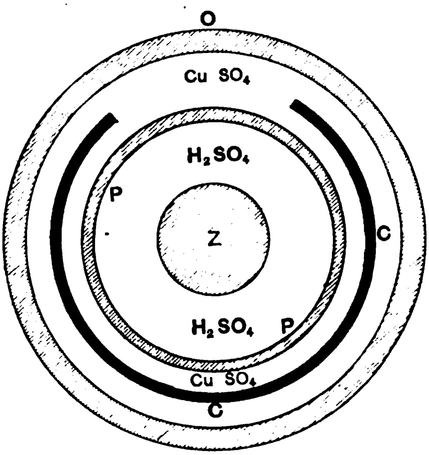


FIG. 20.—PLAN OF DANIELL CELL.

Fig. 21 shows a curve obtained by plotting the third and fourth columns in the above list, and in it we notice at once some very peculiar features. In the early stages of current the resistance appears to drop very rapidly almost along a straight line—down to about 0·3 ampere. At this point the curve bends over, and continues to do so, forming a kind of elbow till a current

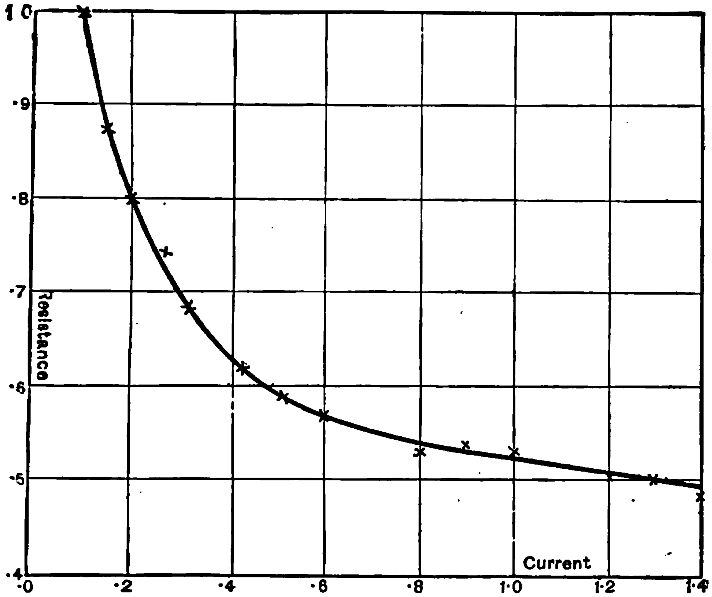


FIG. 21.—CHANGE OF RESISTANCE WITH CURRENT.

of about 0·6 ampere is reached, when it again flattens out and continues along what is practically a second straight line with a slightly downward inclination. The observations were carried up to 1·4 amperes, and the current broken after each reading in order to verify the value of E.

Similar tests were carried out on a large number of cells of different types — Grove, bichromate, Menotto, etc.—and in every case a curve was obtained which did not materially differ from the one shown above. In each case precautions were taken to avoid the effects of polarisation as far as possible, but all the experiments went to prove that the cause of the change was certainly not due to this source.

Knowing that the principal resistance in a cell is due to the electrolyte, Mr. O'Keeffe

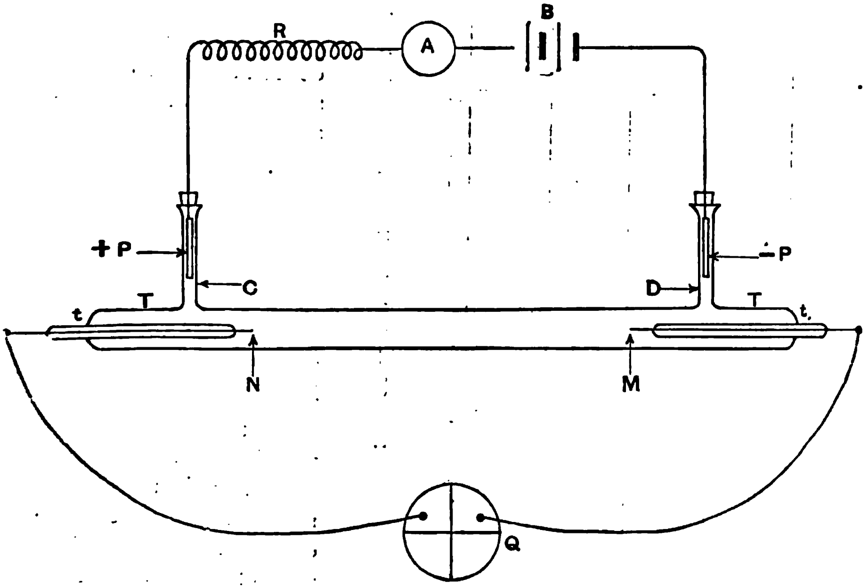


FIG. 22.—MEASUREMENT OF ELECTROLYTIC RESISTANCE.

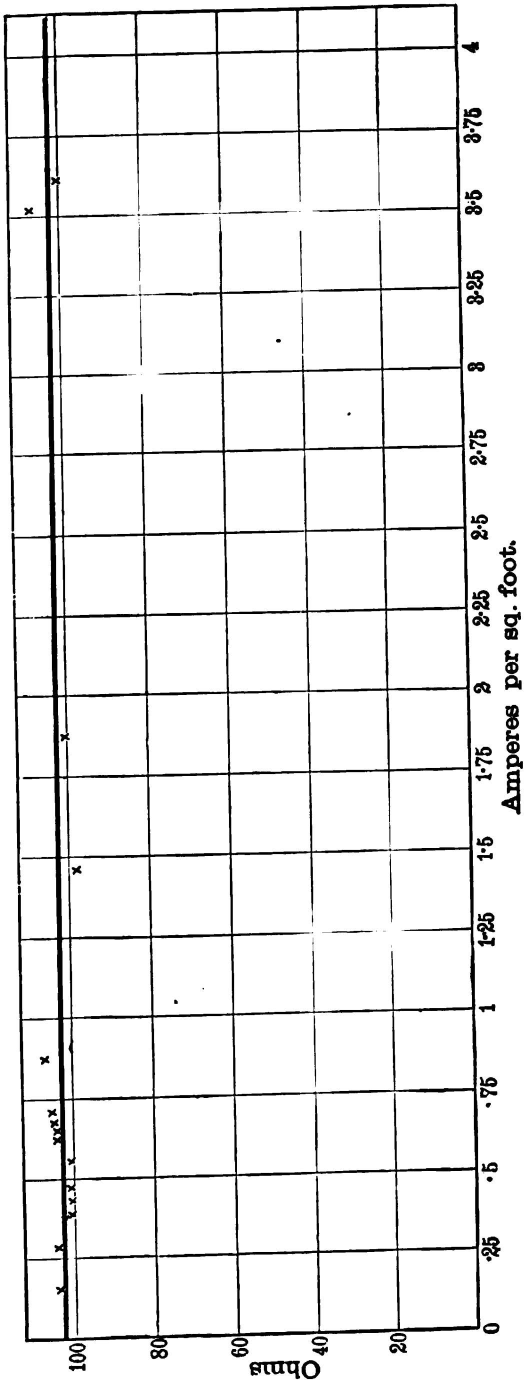


FIG 23.—VARIATION OF RESISTANCE OF AN ELECTROLYTE, WITH VARIATION OF CURRENT DENSITY.

undertook a series of experiments with the object of determining whether or not an electrolyte underwent a change of resistance when currents of different strength were sent through it, and selected sulphuric acid of density about 1·2 as the material to be experimented upon. The general arrangements for carrying out the test are shown in Fig. 22. T T is a horizontal glass tube filled with sulphuric acid, near the ends of which two other short vertical glass tubes C and D are inserted, these latter tubes being open at the top. Into the ends T and T of the horizontal tube two thin glass tubes *t* and *t* are sealed. These tubes contain platinum wires sealed at both ends, and have the functions of making contact with the acid at the points M and N, and with the external circuit at the points *t* and *t*. The acid nearly fills the vertical tubes, and into it dip two platinum electrodes + P and — P. By means of these electrodes any desired strength of current can be sent through the tube; but this is always accompanied by the evolution of hydrogen and oxygen on the negative and positive electrodes respectively; in other words, these electrodes become thoroughly polarised. The points M and N of the platinum wires are situated at a comparatively long distance from the electrodes, and provided no current is drawn from these wires the effect of polarisation at the points is negligible. Q is a quadrant electrometer which, of course, takes no current, and which gives us a measure of the E.M.F. working between the points M and N. We can thus measure the E.M.F. between the points M and N, and if we know the strength of the current flowing we can find the true resistance of the column of liquid between these two points and eliminate all errors due to polarisation. Above the tube is shown the method of adjusting the current. B is a battery consisting of a couple of accumulators, R is a variable resistance for adjusting the strength of current, and A is an ampèremeter for measuring the current. A D'Arsonval galvanometer suitably calibrated was used for measuring the current.

Distance between points M and N = 82 cm.

Distance between points and electrodes = 10 cm. (about).

Area of platinum electrodes = 14 sq. cm.

Section of the tube = 1·244 sq. cm.

The following list gives the results obtained from the tests, and on plotting them in the form of a curve, Fig. 23, we cannot but arrive at the conclusion that the resistance remains quite constant how ever the current may vary.

READINGS TAKEN WITH ASCENDING CURRENT.

VOLTS.	AMPERES.	AMPS. PER SQ. C.M.	AMPS. PER SQ. FOOT.	RESISTANCE (OHMS).
·0236	·0002282	·0001832	0·17	103·3
·0267	·0002524	·0002024	0·188	101·8
·03208	·000308	·0002476	0·2298	104·
·03564	·000346	·0002779	0·258	103·
·0389	·0003748	·000301	0·2799	103·8
·0426	·000408	·000328	0·3048	104·1
·0439	·000423	·00034	0·316	103·8
·0467	·00045	·0003615	0·336	103·7
·04883	·000475	·0003815	0·3548	102·8
·05013	·000495	·0003975	0·3695	101·2
·05257	·000516	·000415	0·385	101·9
·05605	·0005555	·0004465	0·415	100·8
·0594	·000585	·00047	0·437	101·5
·06323	·000619	·000497	0·462	102·1
·06705	·000656	·000527	0·49	102·2
·0718	·000696	·00056	0·5205	103·1
·075	·000743	·000598	0·554	101·
·0817	·0007915	·0006365	0·591	103·1
·0851	·000825	·000664	0·615	103·1
·0886	·000856	·000689	0·64	103·5
·0927	·000892	·000716	0·666	103·9
·0967	·000928	·000746	0·693	104·1
·253	·0025	·002008	1·867	101·1
·475	·00472	·00388	3·6	100·7
·64	·00611	·00491	4·56	104·8

Readings were now taken with a decreasing current:—

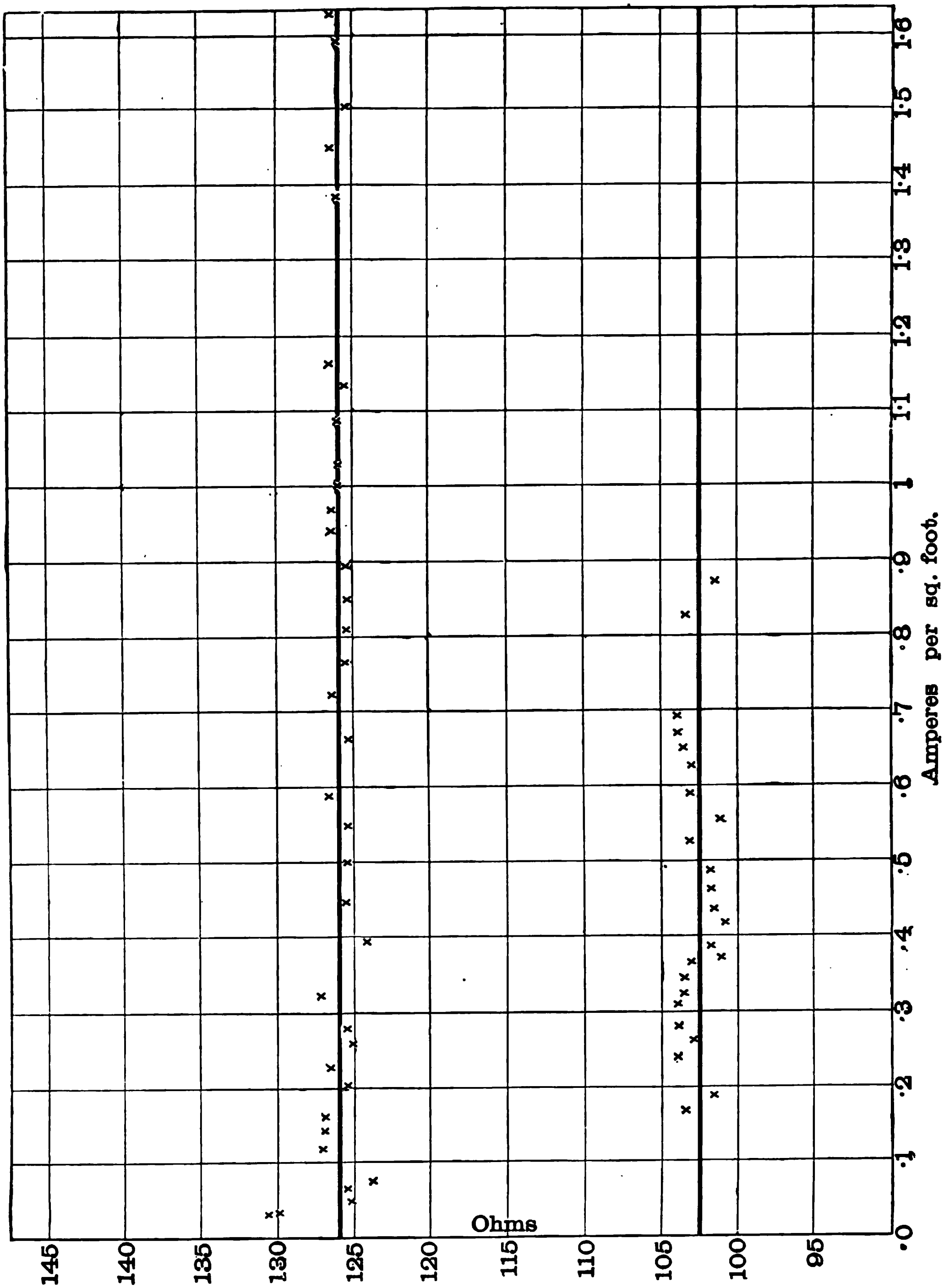
VOLTS.	AMPERES.	AMPS. PER SQ. C.M.	AMPS. PER SQ. FOOT.	RESISTANCE (OHMS).
0·3574	·003498	·002807	2·608	102·1
0·2288	·00222	·001783	1·656	103·1
0·1196	·001179	·000946	0·878	101·4
0·114	·001104	·000888	0·825	103·2
·0921	·000885	·000711	0·6604	104·
·0849	·000816	·0006555	0·609	104·
·0761	·000733	·000589	0·547	103·8
·07105	·0006875	·000553	0·506	103·4
·0645	·000623	·0005005	0·4·66	103·6
·05505	·000541	·000435	0·4·045	101·8
·04715	·000463	·000372	0·3·46	102·
·03901	·000375	·000302	0·2·8	104·

These results are plotted, giving the lower curve of Fig. 24.

Considerable difficulty was experienced in carrying out these tests with the desired degree of accuracy owing to the small changes of deflection on the electrometer which had to be noted, and Mr. Tunbridge, who carried out the tests, suggested the following modification.

EXPERIMENT II.

In order to obtain more accurate results, a high resistance astatic galvanometer was employed as voltmeter. Since this instrument carried a small current, a difficulty presented itself when the potential was taken either at the platinum tips or electrodes, owing to the varying back E.M.F., which was very large compared with the change of potential required to be measured. To obviate this small strips of accumulator plate of 20·8 sq. cm. surface were employed as electrodes, the E.M.F. between these on open circuit being practically constant. These also had the advantage of evolving very little gas. It might be objected that these plates themselves would change in resistance; but then their resistance being so small compared with that of the electrolyte, if it changed to so much as 10 times or $\frac{1}{10}$th its original value the total resistance would not appreciably


Ohms
145
140
135
130
125
120
115
110
105
100
95
Amperes per sq. foot.
·0
·1
·2
·3
·4
·5
·6
·7
·8
·9
1
1·1
1·2
1·3
1·4
1·5
1·6

be affected. An opposing constant E.M.F. was placed in series with the voltmeter circuit, so that on open circuit the deflection of the voltmeter was zero. The arrangement and results were as below :—

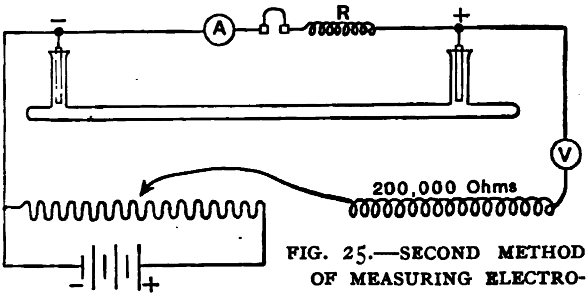


FIG. 25.—SECOND METHOD OF MEASURING ELECTROLYTIC RESISTANCE.

VOLTS.	AMPERES.	AMPS. PER SQ. C.M.	AMPS. PER. SQ. FOOT.	RESISTANCE (OHMS).
·00634	·0000486	·00003905	·0292	130·4
·00793	·0000634	·00005095	·0473	125·2
·01141	·0000909	·000073	·0679	125·8
·01361	·0001099	·0000883	·0821	124·
·01965	·000155	·0001246	·1158	126·8
·0236	·0001863	·0001498	·1390	126·7
·02753	·0002176	·0001748	·1623	126·6
·0339	·00027	·000217	·2017	125·7
·03864	·000306	·0002459	·2284	126·3
·04465	·000357	·000287	·266	125·1
·0485	·0003863	·0003107	·2887	125·4
·05355	·0004223	·0003398	·3157	126·8
·0653	·000525	·000422	·392	124·3
·0751	·000596	·000479	·445	125·9
·084	·000669	·000537	·500	125·7
·0926	·000737	·000592	·550	125·7
·0999	·00079	·000635	·59	126·2
·1106	·000884	·00071	·66	125·2
·1209	·000959	·00077	·717	126·2
·1282	·00102	·00082	·754	125·7
·1359	·00108	·000868	·806	125·8
·1427	·001135	·000912	·848	125·7
·1507	·001198	·000963	·895	125·9
·158	·001251	·001006	·935	126·1
·1628	·001288	·001035	·963	126·3
·1695	·001346	·001082	1·005	126·1
·1752	·00139	·001118	1·038	126·
·1845	·001462	·001177	1·092	126·1
·1908	·001517	·00122	1·132	125·9
·198	·001566	·00126	1·17	126·4
·2324	·001863	·0015	1·39	126·
·2426	·00194	·001559	1·448	126·1
·256	·002035	·001636	1·5	125·8
·268	002127	·00171	1·59	126·
·282	·002237	·001796	1·67	126·
·2973	·002355	·001892	1·757	126·2
·3078	·002435	·001958	1·817	126·3
·3133	·002488	·002	1·86	126·

Readings of the voltmeter were taken when circuit was closed and when open, and the difference taken as proportional to the volts required to drive the current indicated by the ammeter through the electrolyte.

These results give the upper curve in Fig. 24.

The same glass tube was used as in Experiment 1, but the distance between the electrodes was necessarily greater, and hence the increased resistance of the column from about 102·5 to 126 ohms.

These tests seem to prove conclusively that whatever else changes in the cell when different strengths of current are taken from it, *the resistance of the electrolyte remains constant.*

CARBON RESISTANCE FRAME.

In carrying out these experiments and many others, the variable resistance often forms a most important item in the apparatus. We require something capable of carrying large currents as well as small currents, and capable also of changing its value continuously, and not by abrupt jumps.

None of the ordinary resistances in general use will answer these requirements, but the one illustrated in Fig. 26 is the most satisfactory that the author[1] has yet used. The outer frame F F consists of a solid gun-metal casting. (Where magnetic effects are of no importance this may consist of cast iron. It is cheaper and answers its purpose equally well.) The resistance proper consists of a series of carbon plates C C C, of the dimensions $3\frac{1}{2}'' \times 3\frac{1}{2}'' \times \frac{3}{8}''$, through which the current has to pass, and the amount of which is regulated by the closeness with which the plates are squeezed together. If the plates are quite loose, the resistance may be anything up to infinity; whereas if they are

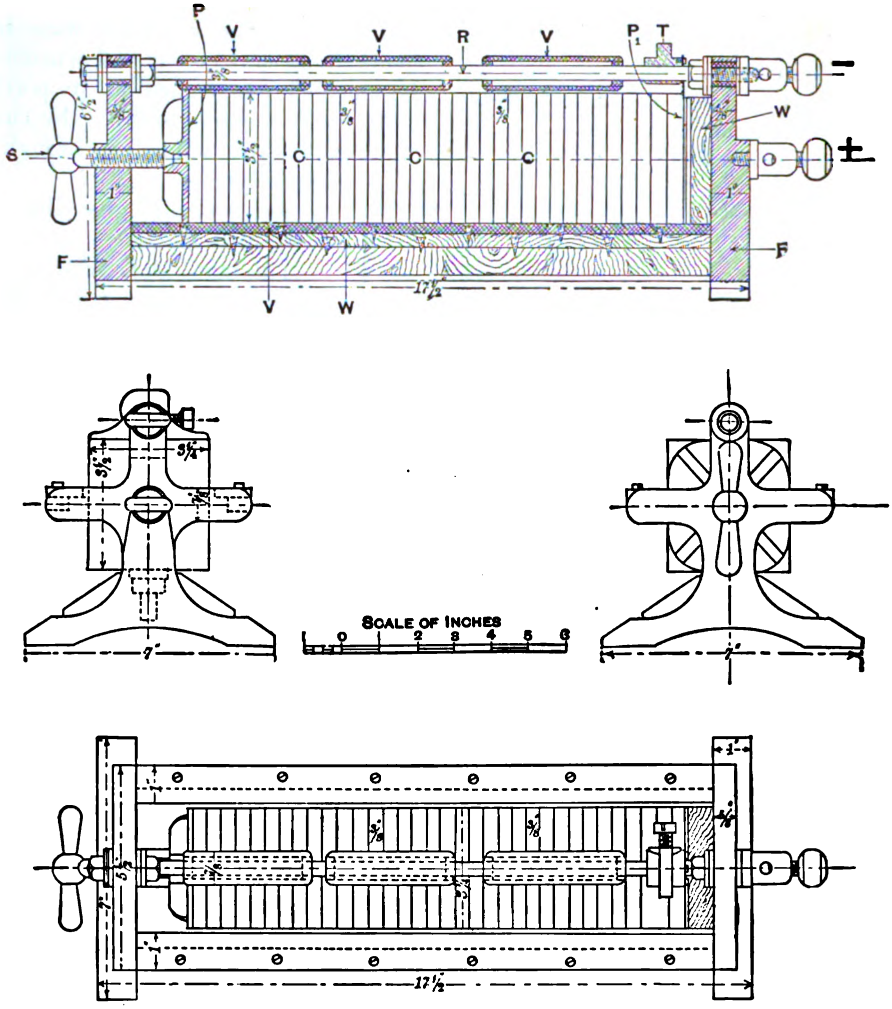


FIG. 26.—RESISTANCE FRAME FOR CARBON PLATES.

tightly squeezed together, the resistance becomes a fraction of an ohm. The tightness or looseness of the plates is regulated by the screw S shown at the left-hand side of the drawing. These plates are carefully insulated from the framework by means of strips of vulcanised fibre V V V, etc., but are in contact with two gun-metal plates P and P, which are shown one at each end of the carbons. One of these plates P is in contact with the screw, and so in contact with the frame of the instrument and the terminal marked + ; the other is in contact with the insulated metal rod R and with the terminal marked −. This rod is insulated from the framework by vulcanised fibre collars, and from the plates by three sections of tube made of the same material. As the resistance frame is shown in the drawing the whole of the carbon plates are in the path of the current; but if very small resistances are required, one of the end plates P can be moved and placed between any pair of carbons, so that the resistance can be reduced till only a single carbon plate remains between the terminals. This change is made by unscrewing the terminal T from the rod R and moving it to any desired position.

Currents up to a hundred or more ampères can be sent through one of these frames for a short time without injuring it, and the resistance can be varied *continuously* from the minimum up to infinity. For strong currents a number of these in parallel will be found useful, and, unlike most other resistances for large currents, they do not deteriorate quickly in use. They are suitable for a current of about 10 amperes for a prolonged time without overheating.

The working drawings shown in Fig. 26 are the design of Mr. E. Rousseau, of Finsbury Technical College, who is a pioneer in this class of work. Where it is desired to produce a very even variation over a fairly wide range, it is preferable to connect several frames in series, so that when the maximum desired resistance is attained the plates do not have to be excessively loose.

QUALIFICATIONS OF A GOOD BATTERY.

A good primary battery should possess as many as possible of the following qualifications :—

1. Its E.M.F. should be as high as possible and constant.
2. Its resistance should be as low as possible.
3. It should be free from polarisation.
4. It should be free from local action.
5. The materials should be inexpensive and durable.
6. It should not require frequent attention or renewals of materials.
7. It should not give off noxious or corrosive fumes.

It is needless to say that no single cell possesses all these desirable qualities, but fortunately they are not all required for certain classes of work. Of the various cells in general use, each is probably the best suited to a particular class of work, though it might be utterly useless for another class.

CHAPTER II.—TYPES OF CELLS.

CLASSIFICATION OF CELLS—THE GROVE CELL—THE BICHROMATE CELL—FULLER'S BICHROMATE—THE LECLANCHÉ CELL—CELLS IN WHICH POLARISATION IS PREVENTED BY ELECTRO-CHEMICAL MEANS—STANDARD CELLS—FLEMING'S STANDARD CELL.

CLASSIFICATION OF CELLS.

Polarisation plays such an important part in the working of primary batteries that it seems best to classify cells according to the devices which have been adopted for diminishing or eliminating it. These devices can be grouped under three broad headings, so that we have the following four classes :—

1. Cells in which no attempt is made to prevent polarisation.
2. Cells in which polarisation is prevented by purely mechanical means.
3. Cells in which polarisation is prevented by chemical means.
4. Cells in which polarisation is prevented by electro-chemical means.

CLASS I.

The cell illustrated in Fig. 17 is the typical cell of this class, and, notwithstanding its many defects, it possesses some qualities which render it suitable for a certain class of work. Starting with an E.M.F. of about 1 volt, it passes through a variable stage in which polarisation reduces the E.M.F. to about one-third of a volt, and at the same time increases its resistance ; but having arrived at the completely polarised state, these two quantities attain fixed values, and during the further working of the cell we can rely upon their remaining almost absolutely constant. The low E.M.F. makes it very inefficient, but in many cases efficiency is of less importance than constancy.

CLASS II.

None of the cells belonging to this class can be said to do their work in a thoroughly satisfactory manner. Polarisation is only partially prevented, and though the E.M.F. does not fall as low as in those of Class I., still it always falls below its initial value, and remains variable. Amongst the devices which have been adopted, the following are perhaps the most successful:—

(*a*) Blowing air into the aliment, and thus keeping it in a constant state of agitation. Any large accumulation of hydrogen on the negative element is thus prevented, and a portion of the plate is kept comparatively clean. The method is purely fanciful, and has no practical value.

(*b*) Constructing the negative elements in the form of large discs, and mounting them on a spindle which is made to revolve when the battery is at work. The spindle being on a level with the surface of the liquid, only half the plate is immersed, and the other half is passing through the air. The hydrogen accumulates in the usual way on the portion which is in the liquid, but passing into the air some unites with the oxygen of the air, and some escapes, and the plate again enters the liquid in a partially clean condition.

(*c*) The device which gave the best results was that suggested by Smee. In his cell the negative element consisted of a platinum plate, upon which platinum, in the form of a fine black powder, was electrically deposited. The resulting plate had a rough granular surface. In work, the hydrogen is evolved on this plate, but collects in the form of bubbles on the small projecting portions, and when these bubbles attain a certain size they break off and rise through the liquid. The recesses remain almost free from the gas, and thus to some extent check polarisation. The platinum plate is, of course, an expensive item in the cell, but a cheaper plate can be made which will work equally well. It consists of a copper plate upon which a granular coating of copper is deposited electrically; upon this a thin coat of silver is plated, and finally a coat of platinum. The resulting plate behaves in every respect as if it consisted of pure platinum.

CLASS III.

Such is the tenacity with which the hydrogen adheres to the negative element that it would seem impossible entirely to remove it by any mechanical means. The plate may be removed from the liquid when once polarised, thoroughly rubbed with a cloth or scrubbed with a brush, and on returning it to the liquid it will still show evidence of hydrogen on its surface. What cannot be done by mechanical means can, however, be easily accomplished by chemical. All that it is necessary to do is to surround the element with some substance rich in oxygen, and which easily parts with it. This oxygen unites with the hydrogen to form water, and the plate is thus left free.

The oxidising agents most generally used are nitric acid, manganese dioxide, and bichromate and permanganate of potash, but the use of these materials introduces a fresh complication in the construction of the cell. If they will freely unite with hydrogen, it is clear that they will unite more readily with zinc, which is the better fuel, and unless special arrangements are made the zinc would be quickly consumed when the cell was doing no useful work. Where the depolarising agent is a solid, there is no special difficulty in keeping it away from the zinc; but when it consists of a liquid, as is generally the case, it is usually placed with the negative element in a semi-porous pot, which is immersed in the liquid that surrounds the zinc. The positive element is thus immersed in the aliment, and the negative in the depolarising agent, whilst the two liquids are kept from mixing by means of the porous pot. The negative element must consist of some substance having a very low heat value, otherwise it would be attacked and burnt up by the oxidising agent. For this reason platinum and carbon, which both have very low heat values, are the substances most used.

THE GROVE CELL.

Sir William Grove, so long ago as 1838, showed, in the cell named after him, how to check polarisation effectually and at the same time procure a high E.M.F. The cell is made up in a number of different forms, but the one illustrated in Fig. 27 will be found very convenient. The outer vessel (which is partly cut away in the figure) is made of ebonite, having the dimensions 5″ × 3″ × 2″.

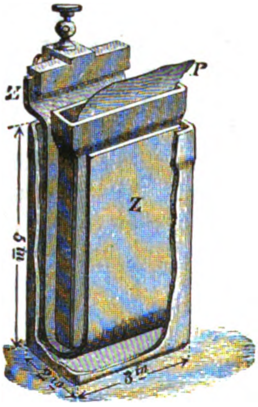


FIG. 27.—GROVE CELL.

The positive element consists of an

amalgamated zinc plate Z Z, bent into the form of a **U** so as to utilise both sides of the negative element and thereby considerably decrease the resistance of the cell. This is immersed in an aliment consisting of ten parts of water to one of sulphuric acid.

The negative element consists of a rectangular platinum sheet P of the dimensions 5½" × 2½" × 0·002", and is immersed in a depolarising agent consisting of strong nitric acid. These are both contained in a porous pot consisting of unglazed earthenware, which rests in the bend formed in the zinc plate.

In this cell, polarisation is entirely prevented so long as the nitric acid remains strong. Its E.M.F. is as high as 1·95 volt, and its resistance as low as 0·15 ohm, so that on short circuit it can give a current of some 13 amperes. In working, the sulphuric acid gradually becomes converted into sulphate of zinc, and the nitric acid becomes diluted by the formation of water. This diluting of the nitric acid has a twofold effect on the cell—it lowers the E.M.F. gradually from 1·95 volt at starting to about 1·5 volt when the cell is fairly run down, and increases its resistance from 0·15 at starting to 1 ohm or even 1·5 ohms when run down. The chemical action which takes place when the cell is at work is—

$$\underset{\text{Zinc}}{Zn} + \underset{\text{Sulphuric acid}}{H_2SO_4} + \underset{\text{Nitric acid}}{2HNO_3} + \underset{\text{Platinum}}{Pt}$$

$$= \underset{\text{Zinc sulphate}}{ZnSO_4} + \underset{\text{Water}}{2H_2O} + \underset{\text{Nitrogen peroxide}}{N_2O_4} + \underset{\text{Platinum}}{Pt}$$

The zinc is consumed in order to form zinc sulphate with the aliment, the aliment is converted from sulphuric acid into sulphate of zinc, and hydrogen is set free. In the ordinary way this hydrogen would be deposited on the platinum, but before reaching that it meets the nitric acid, with which it unites to form water and nitrogen peroxide. This nitrogen peroxide is a gas which, however, does not polarise, as it is freely soluble in nitric acid. It also falls off into the atmosphere in the form of the objectionable red fumes which characterise the working of the Grove cell; in fact, they render the cell quite unsuited for most kinds of indoor work.

The cell is suitable for giving strong currents continuously where the fumes permit its use, but for any kind of intermittent work it is useless. The initial cost of the cell is heavy, owing to the platinum plate, but this plate will last for an indefinite time, and as there is very little waste of materials in the cell it is fairly economical. The effect of a rise of temperature in the cell is to increase its E.M.F., and to decrease its resistance.

THE BICHROMATE CELL.

This cell is made up in a number of different forms, one of which, illustrated in Fig. 28, is known as the bottle type. It consists of a glass flask, on the neck of which is fixed a brass collar, carrying an ebonite disc on which are placed the brass terminals B B. Through the centre of this disc passes a brass rod A, which carries at its lower end the positive element in the shape of the zinc plate Z. This rod,

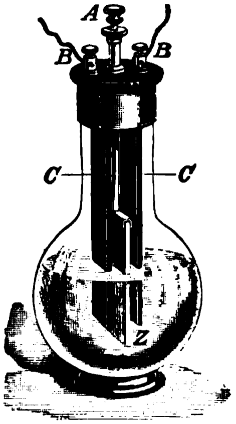


FIG. 28.—BOTTLE FORM OF BICHROMATE CELL.

which is attached to one of the terminals, can slide freely up or down so as to raise the zinc out of the liquid when the cell is not at work. The negative element consists of the pair of carbon plates C C, which are parallel to the zinc, and which thereby utilise both its sides and diminish the resistance of the cell.

The same liquid acts both as aliment and depolarising agent, and consists of a mixture of sulphuric acid, bichromate of potash, and water, in the following proportions :—

$$\left.\begin{array}{lr}\text{Sulphuric acid} & 2\\ \text{Bichromate of potash} & 1\\ \text{Water} & 12\end{array}\right\}\text{ by weight.}$$

The mixture is best made by first crushing the crystals of bichromate of potash to a fine powder; which should be slowly added to the required quantity of sulphuric acid ; cold water is then slowly added. This brings about a considerable evolution of heat, and, as this is to be avoided as far as possible, the process is necessarily a tedious one. The resulting mixture must be allowed to cool thoroughly before being used in the cell.

For small and intermittent work this cell is in many respects extremely good. It possesses a high E.M.F.—about 2 volts—which remains fairly constant, and a very low resistance, owing to the good conducting power of the constituents and the short distance between the plates. It is therefore suitable for giving an extremely heavy current. It possesses the further advantage of not giving off any noxious fumes like the Grove and Bunsen. When kept on continuous work the E.M.F. gradually falls, but if allowed to rest for a short time it quickly recovers its original value.

The liquid not only consumes the zinc when the circuit is closed and a current is being drawn from the cell, but it also attacks it when the circuit is open. In fact, if the zinc be allowed to remain standing in the liquid it will quickly get entirely consumed by local action. For this reason the zinc is raised out of the liquid the instant the cell ceases to be required for current-giving purposes. This, of course, is a serious fault in the cell, as any oversight in raising the zinc out of the strongly oxidising solution results in the total consumption of the zinc.

The reaction that occurs in the working of the cell may be expressed thus :—

$$\underset{\text{Zinc}}{3Zn} + \underset{\text{Sulphuric acid}}{6H_2SO_4} + \underset{\text{Chromic acid}}{2CrO_3} + \underset{\text{Carbon}}{C}$$
$$= \underset{\text{Zinc sulphate}}{3ZnSO_4} + \underset{\text{Water}}{6H_2O} + \underset{\text{Chromium sulphate}}{Cr_23(SO_4)} + \underset{\text{Carbon}}{C}$$

It will thus be seen that the zinc unites with the sulphuric acid to form zinc sulphate ; another portion of the sulphuric acid unites with the chromic acid to form chromium sulphate, whilst the hydrogen set free from the sulphuric acid unites with the oxygen set free from the chromic acid to form water—the carbon remaining unacted upon and free from hydrogen so long as the solution does not become too weak.

The net result of the action thus amounts to :—

(*a*) The consumption of zinc and the formation of zinc sulphate.

(*b*) The substitution of chromium sulphate for chromic acid.

(*c*) The substitution of water for sulphuric acid.

The solution thus becomes diluted, and the E.M.F. of the cell falls off accordingly.

The original colour of the solution is a rich orange, and so long as it retains that colour the cell is in good working order. As it becomes exhausted the colour changes to a bluish tint. If the E.M.F. falls while the solution retains the orange tint, it can quickly be rectified by the addition of a little strong sulphuric acid.

A form of this cell brought out by Trouvé gave very strong currents, and was much used in the early days of glow lamps. He used a number of large rectangular boxes connected up in a manner suitable for the work in hand, and had a special device for raising or lowering all the zincs together. The solution used was made up as follows :—

	By weight.
Sulphuric acid	27
Bichromate of potash	18
Water	120

With the exception of the slight difference in the proportion of materials in the solution, the cell differed only in mechanical details from the bottle form already described.

The great objection to the use of cells of this class lay in the fact that local action was always a prominent feature ; and if by any chance the zincs were allowed to remain in the solution for any considerable time when the cell was out of use, they would be completely eaten away. A form of the cell brought out by Fuller completely obviated this objectionable feature.

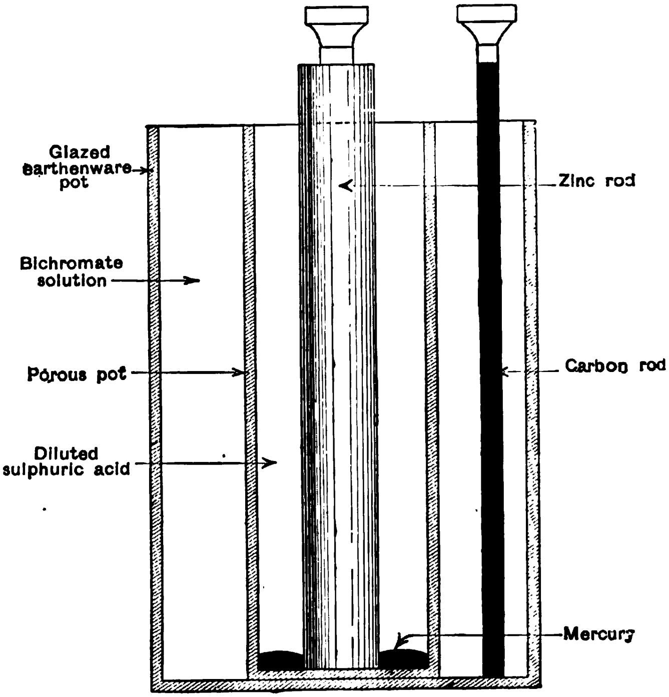


FIG. 29.—FULLER'S BICHROMATE CELL.

FULLER'S BICHROMATE.

This cell is excellent in all respects, and is most useful for small work about a laboratory when a higher E.M.F. than that of a Daniell is wanted.

A section through this cell, shown in Fig. 29, sufficiently explains its working. The outer vessel consists of a circular glazed earthenware vessel, containing a solution made up in the following proportions :—

Sulphuric acid	50	by weight.
Bichromate of potash	100	
Water	1000	

In this solution is placed one or more carbon plates or rods, which form the negative element. The porous pot contains a dilute solution of sulphuric acid, in which is permanently immersed a thoroughly amalgamated zinc rod, the amalgamation being insured by the end of the rod dipping into a small pool of mercury. This cell has the same E.M.F. as the other types, but owing to the porous pot, the long distance between the elements, and the comparatively small size of the carbon its resistance is considerably greater. It, however, possesses the enormous advantage over the others that it can be left set up and out of work without any appreciable consumption of the zinc.

The dilution of the solution in all the cells of this section renders the oxidising action less and less effective, and a time arrives when polarisation occurs in a marked degree. Even when at their best, these cells are never quite free from polarisation, though it does not play anything like an important part until they have been nearly run down.

THE LECLANCHÉ CELL.

The depolarising agent in the cells described has in each case been a liquid, and one which attacked the zinc whether the cell was in use or not. In the Leclanché cell it consists of a solid, manganese dioxide, and one which has no action on the zinc, however long the cell is out of use. The form in which this cell is usually made up is illustrated in Fig. 30. The outer vessel consists of a square-bottomed glass jar, the upper portion of which is narrowed, allowing sufficient room for the porous pot to pass freely in ; a small lip is also allowed for the zinc rod to pass through, and which is also convenient for filling or emptying the jar. The square shape of the jar allows a number of them to be stowed in a small space without any waste of room, and the narrowing of its upper portion reduces the evaporation of the liquid to the smallest possible amount.

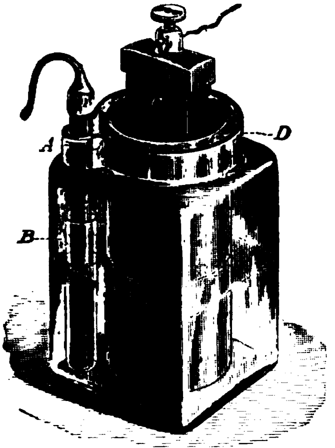


FIG. 30.—LECLANCHÉ CELL.

The positive element consists of a circular zinc rod A, and the aliment is a strong solution of sal-ammoniac B. The negative element is a carbon plate C, which is placed in a porous pot D, and surrounded with a mixture of manganese dioxide and carbon in equal parts. The manganese dioxide acts as the depolarising agent, and is the one solid substance which is in general use for this purpose. The porous pot is used for the sole purpose of keeping the negative element surrounded with the mechanical mixture of manganese and carbon, and in some forms of the cell this pot is omitted.

Drawn zinc of about half an inch in diameter is the best kind to use for the positive element. Cast zinc is crystalline in structure, very brittle, very porous, and invariably contains a large number of impurities ; it is consumed very irregularly during the working of the cell. Rolled zinc is far less porous ; it is not, however, uniformly attacked by the liquid, as may be seen by small scales forming on its surface. Rolled zinc is much better than cast, but is inferior to drawn zinc, which is much more homogeneous than either. Where the zinc is irregularly consumed, non-conducting crystals form on the roughened surface, which decreases the effective surface of the zinc and increases the resistance of the cell.

It is not customary to amalgamate the zinc rods, but though this precaution may not be necessary where the best drawn zinc is used, it is undoubtedly advisable to amalgamate the zincs usually sold with Leclanché cells. These zincs are seldom drawn, and though they are not attacked by the liquid when the cell is not working, still they are irregularly eaten away when the cell does work, and saline crystals form at the irregularities thus exposed, instead of dropping innocently to the bottom of the cell as they would otherwise have done. Amalgamation insures that the zincs will be consumed fairly uniformly.

The aliment should consist of a saturated or nearly saturated, solution of sal-ammoniac; and it is of importance that it should be as pure as possible. The sal-ammoniac purified by sublimation is rather expensive, but is extremely good. If the solution is too weak, it is unable to dissolve the crystals of oxychloride of zinc which are formed by the working of the cell, and then deposit on the zinc rods; a fairly strong solution, however, dissolves them readily and keeps the zincs clean. On the other hand, if too much sal-ammoniac is present it will crystallise on the zinc and be as injurious as if the solution were too weak. Either too much or too little sal-ammoniac will produce non-conducting crystals on the zinc, which will considerably increase the resistance of the cell. The cell should not be much more than half filled with this liquid.

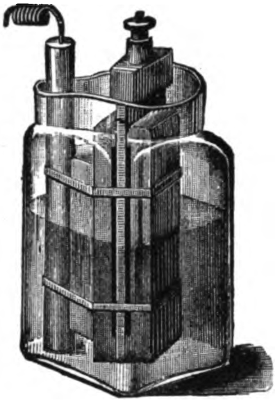


FIG. 31.—AGGLOMERATE LECLANCHÉ CELL.

The porous pot is nothing more than a mechanical contrivance for keeping the mixture of manganese and carbon in its place, and is not used—as is usually the case—for separating two liquids. It should be as porous as possible, and on no account should it be allowed to come into contact with the zinc. A couple of rubber rings on the zinc will effectually prevent this.

The space round the negative element is tightly packed with a mixture of manganese peroxide and carbon. The best manganese to use for this purpose is that known as the needle variety; it is crystalline in structure, presents a silky appearance, is extremely hard, and has a comparatively low resistance. In order to make the mixture, the manganese should be crushed, and all the powdered portion removed, leaving only that which is in a fine granular state; this should then be mixed with an equal amount of granular carbon, and the mixture thus obtained should be forced into the vacant space in the porous pot.

The grains of carbon may be much larger than those of the manganese, but no powdered material should on any account be used. Both the manganese and the carbon are better conductors than the liquid which fills all the spaces between them, and for this reason the mixture should be as tightly packed as possible, so as to fill the space with good, instead of bad, conducting material.

Manganese dioxide is a substance rich in oxygen, which it gives up slowly at the ordinary temperature, but quickly on the application of heat. When used as a depolarising agent—as it is used in the Leclanché cell—it does its work very slowly, but at the same time it does it very thoroughly.

A modified form of the Leclanché cell, known as the **AGGLOMERATE TYPE**, is illustrated in Fig. 31. Since the resistance of the cell increases with the distance between the elements, and decreases as the mixture is more tightly packed, it is clearly of advantage to have the elements as close as possible, and to have the mixture as tightly packed as possible. Both these objects are attained in the agglomerate form, which also dispenses with the use of the porous pot. The mixture is made into slabs or blocks, one of which is placed on each side of the carbon plate, and the whole strapped together by two rubber bands. This arrangement is shown in Fig. 31, which also shows the manner in which the zinc rod is prevented from touching the block by interposing a piece of wood between them.

The composition of the depolarising blocks is as follows :—

Manganese dioxide	40	parts
Carbon	52	„
Gum	5	„
Bisulphate of potash	3	„

The bisulphate of potash is added in order to dissolve the zinc salts which form in the pores of the mixture. The gum is added in order to bind the whole together into a compact mass. This mixture is heated to about 100° Cent., and then subjected to hydraulic pressure, with the result that slabs of any desired size and shape can be easily obtained. The resistance of this type is less than that of the ordinary form, and its E.M.F. is the same —about 1·45 at starting.

There is some difficulty experienced in making a good connection with the carbon plate, and the following device is usually adopted. The upper portion of the plate is first thoroughly soaked in paraffin wax at a temperature of about 110° Cent., and two holes having been drilled through it, a lead cap is then cast on to it, as shown in Figs. 30 and 31 ; a brass terminal is then fixed into the lead cap. The plate is soaked in paraffin in order to prevent the liquid from creeping up through the pores and attacking the lead at the junction with the carbon. If such creeping did occur, lead salts would be formed at the junction, gradually introducing resistance into the circuit, and finally result in the destruction of all connection between the carbon and lead.

For a short time the Leclanché cell can send a fairly strong current, but it quickly polarises, and its E.M.F. consequently falls; in other words, it runs down rapidly when kept at continuous work. If the cell be now allowed to rest for a time and again tested, it will be found to have regained its original E.M.F., which in an exactly similar manner will again run down by use.

The explanation of this phenomenon is that the negative element becomes coated with hydrogen during the working of the cell, and polarisation therefore ensues ; but when the cell is then allowed to rest, the manganese dioxide gives up a portion of its oxygen, which unites with the hydrogen on the carbon to form water, and the cell is thus restored to its original state.

The chemical action which occurs may be thus expressed (but it must be remembered that this action occurs in different stages) :—

$$\underset{\text{Zinc}}{Zn} + \underset{\text{Sal-ammoniac}}{2(NH_4Cl)} + \underset{\text{Manganese dioxide}}{MnO_2} + \underset{\text{Carbon}}{C} =$$

$$\underset{\text{Chloride of zinc}}{ZnCl_2} + \underset{\text{Ammonia}}{2NH_3} + \underset{\text{Water}}{H_2O} + \underset{\text{Manganese sesquioxide}}{Mn_2O_3} + \underset{\text{Carbon}}{C}$$

It will be seen that the carbon remains unchanged ; that the manganese dioxide gets converted into manganese sesquioxide ; that the sal-ammoniac gets converted into ammonia and water ; and that the zinc unites with the chlorine to form chloride of zinc. If the solution is too weak, insoluble oxide of zinc will be formed instead of chloride of zinc, and will give the liquid a milky appearance; but this fault can be remedied by the addition of some crystals of sal-ammoniac to the solution.

This cell gives off ammonia only ; it requires no attention for months, and even then it only requires the addition of a little water to replace that which has evaporated. Its resistance increases comparatively slightly below freezing-point, and the liquid does not freeze at ordinary low temperatures. It is useless for giving continuous currents for any length of time, but for any kind of intermittent work requiring strong currents for short times this cell is both effective and economical. There is scarcely any other cell used for ringing electric bells, and there is no other cell that would do the work as well.

It will be noticed that the zinc gets eaten away a little below the surface of the liquid, and finally breaks off at that point, thus entailing a considerable waste. In order to avoid this waste the zinc may be enclosed in a loose glass tube, one end of which rests on the bottom of the cell and the other projects some distance out of the liquid. In this case the zinc gets attacked from the bottom and is gradually eaten away upwards and in a uniform manner. The resistance of the cell is considerably increased by the adoption of this device, but there are many situations where this is a matter of minor importance.

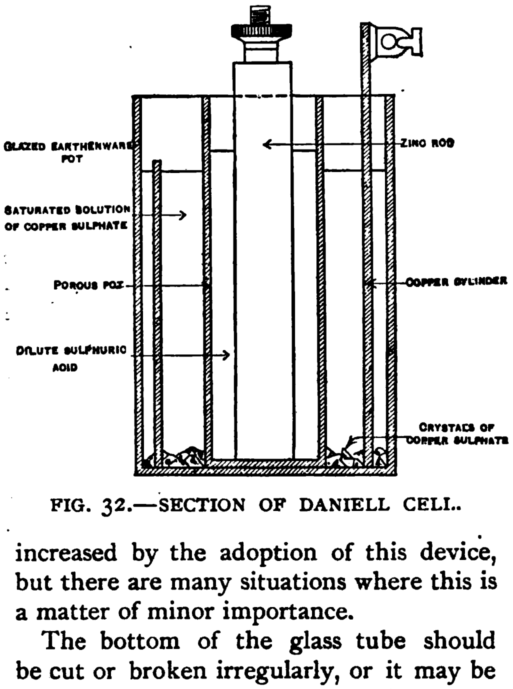


FIG. 32.—SECTION OF DANIELL CELL.

The bottom of the glass tube should be cut or broken irregularly, or it may be cut at an angle with the axis of the tube.

CLASS IV.

CELLS IN WHICH POLARISATION IS PREVENTED BY ELECTRO-CHEMICAL MEANS.

So long as the cells belonging to this class are in anything like fair condition, they are quite free from polarisation, a result which is attained by surrounding the negative element by a solution of its own salt. When a current is passing, this salt is decomposed, and the hydrogen which is set free from the sulphuric acid, instead of being deposited and polarising, unites with the decomposed salt, and allows the metal to be deposited on the negative element. The Daniell is the typical cell of this class, and is made up in a large number of different forms according to the class of work for which it is intended. The form illustrated in Fig. 32 has been found suitable for ordinary rough work.

The containing vessel consists of a glazed earthenware jar, and contains a saturated solution of copper sulphate. This sulphate is kept in a saturated condition by the layer of crystals of copper sulphate lying at the bottom of the jar. In this sulphate is placed a copper plate, bent so as to form about three-fourths of a cylinder, and having a projecting lug upon which is fastened a terminal. Inside this is placed a porous pot which contains dilute sulphuric of the strength of 1 in 10, and in this is immersed a well-amalgamated zinc rod to form the positive element.

On completing the circuit the zinc gets attacked by the sulphuric to form sulphate of zinc, and hydrogen is set free. This hydrogen in the ordinary cell would be deposited on the negative element, but in this case before it can reach the copper it comes in contact with the solution of copper sulphate, which it immediately decomposes and unites with to form sulphuric acid. Pure copper is thus set free from the copper sulphate and is deposited in a uniform layer on the copper plate. So long as the copper sulphate solution is kept up to strength no hydrogen can reach the copper, and consequently the E.M.F. of the cell remains constant. The reaction which occurs can be represented chemically thus :—

$$\underset{\text{Zinc}}{Zn} + \underset{\text{Sulphuric acid}}{H_2SO_4} + \underset{\text{Copper sulphate}}{CuSO_4} + \underset{\text{Copper}}{Cu}$$

$$= \underset{\text{Zinc sulphate}}{ZnSO_4} + \underset{\text{Sulphuric acid}}{H_2SO_4} + \underset{\text{Copper}}{2Cu}$$

Looked at from the values of the metals as fuels, we see that zinc, having a higher heat value than hydrogen, will replace it in the sulphuric acid and form zinc sulphate; the hydrogen thus set free, having a higher heat value than the copper, will replace it in the solution of copper sulphate and form sulphuric acid, whilst the copper thus set free is deposited in a finely divided state on the copper plate. The net result of the reaction then comes to:—

1. The consumption of zinc.
2. The conversion of sulphuric acid into zinc sulphate in the outer vessel.
3. The conversion of sulphate of copper into sulphuric acid in the porous pot.
4. The deposition on the negative element of a layer of finely divided copper.

The porous pot is merely used to prevent the two liquids from mixing, and though it performs this function successfully for a short time, it fails to keep them apart when the cell is allowed to stand for a considerable time. When this happens, the copper sulphate slowly diffuses into the inner vessel, where it comes into contact with the zinc rod, and is there decomposed, the zinc taking the place of the copper in the solution, and the copper being deposited on the zinc rod. This deposit takes place on the zinc as a kind of black mud, and immediately gives rise to local action. It takes place most freely at the base of the zinc, where the distance separating the two is a minimum, being the thickness of the bottom of the porous pot. In order to check this action the bottom of the porous pot is often made non-conducting by heating it before use and immersing it in melted paraffin wax.

The resistance of this form of cell varies from about one-third of an ohm to one ohm, and its E.M.F. remains nearly constant for a long time, even when the cell is subjected to hard work. The E.M.F. depends upon the densities of the two solutions, varying between 1 volt and 1·15 volt. The greater the density of the copper sulphate the higher is the E.M.F., and the greater the density of the zinc sulphate the lower does it become. As both solutions are constantly undergoing a change of density when the cell is at work, it is clear that the E.M.F. varies continually within small limits, in accordance with this change. When the densities of the two solutions are the same, and when the elements are chemically pure, the E.M.F. of the cell is 1·104 volt.

Within a large range of temperature the E.M.F. of this cell remains constant.

STANDARD CELLS.

The possession of a trustworthy standard of E.M.F. is in testing work a matter of primary importance, and none of those that have been described has the necessary qualifications. Further reference to standard cells is made in Sec. V., but the Clark and Fleming cells will be described here in detail. The standard cell almost universally adopted is that due to Clark, and the following are the instructions approved by the Board of Trade for its construction:—

DEFINITION OF THE CELL.

The cell consists of zinc and mercury in a saturated solution of zinc sulphate and mercurous sulphate in water, prepared with mercurous sulphate in excess, and is conveniently contained in a cylindrical glass vessel.

PREPARATION OF THE MATERIALS.

1. *The Mercury.*—To secure purity it should be first treated with acid in the usual manner, and subsequently distilled *in vacuo.*

2. *The Zinc.*—Take a portion of a rod of pure redistilled zinc, solder to one end a piece of copper wire, clean the whole with glass paper or a steel burnisher, carefully

removing any loose pieces of the zinc. Just before making up the cell dip the zinc into dilute sulphuric acid, wash with distilled water, and dry with a clean cloth or filter paper.

3. *The Mercurous Sulphate.*—Take mercurous sulphate, purchased as pure, mix with a small quantity of pure mercury, and wash it thoroughly with cold distilled water by agitation in a bottle ; drain off the water, and repeat the process at least twice. After the last washing, drain off as much of the water as possible.

4. *The Zinc Sulphate Solution.*—Prepare a ***neutral*** saturated solution of pure ("pure recrystallised") zinc sulphate by mixing in a flask distilled water with nearly twice its weight of crystals of pure zinc sulphate, and adding zinc oxide in the proportion of about 2 per cent. by weight of the zinc sulphate crystals to neutralise any free acid. The crystals should be dissolved with the aid of gentle heat, but the temperature to which the solution is raised should not exceed 30° C. Mercurous sulphate treated as described in 3 should be added in the proportion of about 12 per cent. by weight of the zinc sulphate crystals to neutralise any free zinc oxide remaining, and the solution filtered, while still warm, into a stock bottle. Crystals should form as it cools.

5. *The Mercurous Sulphate and Zinc Sulphate Paste.*—Mix the washed mercurous sulphate with the zinc sulphate solution, adding sufficient crystals of zinc sulphate from the stock bottle to ensure saturation, and a small quantity of pure mercury. Shake these up well together to form a paste of the consistence of cream. Heat the paste, but not above a temperature of 30° C. Keep the paste for an hour at this temperature, agitating it from time to time, then allow it to cool ; continue to shake it occasionally while it is cooling. Crystals of zinc sulphate should then be distinctly visible, and should be distributed throughout the mass ; if this is not the case, add more crystals from the stock bottle, and repeat the whole process.

This method ensures the formation of a saturated solution of zinc and mercurous sulphates in water.

Contact is made with the mercury by means of a platinum wire about No. 22 gauge. This is protected from contact with the other materials of the cell by being sealed into a glass tube. The ends of the wire project from the ends of the tube ; one end forms the terminal, the other end and a portion of the glass tube dip into the mercury.

TO SET UP THE CELL.

The cell may conveniently be set up in a small test tube of about 2 cm. diameter and 6 or 7 cm. deep. Place the mercury in the bottom of this tube, filling it to a depth of, say, 0·5 cm. Cut a cork about 0·5 cm. thick to fit the tube ; at one side of the cork bore a hole through which the zinc rod can pass tightly ; at the other side bore another hole for the glass tube which covers the platinum wire ; at the edge of the cork cut a nick through which the air can pass when the cork is pushed into the tube. Wash the cork thoroughly with warm water, and leave it to soak in water for some hours before use. Pass the zinc rod about 1 cm. through the cork.

Clean the glass tube and platinum wire carefully ; then heat the exposed end of the platinum red hot, and insert it in the mercury in the test tube, taking care that the whole of the exposed platinum is covered.

Shake up the paste and introduce it without contact with the upper part of the walls of the test tube, filling the tube above the mercury to a depth of rather more than 2 cm.

Then insert the cork and zinc rod, passing the glass tube through the hole prepared for it. Push the cork gently down until its lower surface is nearly in contact with the liquid. The air will thus be nearly all expelled, and the cell should be left in this condition for at least twenty-four hours before sealing, which should be done as follows.

Melt some marine glue until it is fluid enough to pour by its own weight, and pour it into the test tube above the cork, using sufficient to cover completely the zinc and soldering. The glass tube containing the platinum wire should project some way above the top of the marine glue.

The cell thus set up may be mounted in any desirable manner. It is convenient to arrange the mounting so that the cell may be immersed in a water bath up to the level of, say, the upper surface of the cork. Its temperature can then be determined more accurately than is possible when the cell is in air.

In using the cell sudden variations of temperature should as far as possible be avoided.

FLEMING'S STANDARD CELL.

This cell, which is a modified Daniell, is illustrated in Fig. 33. It consists of a large U tube of ¾ inch in diameter, and about 8 inches long in each limb; out of this open four side tubes, A, B, C and D, and the whole is mounted upon a vertical board as shown. The upper ends of the U tube are closed by the vulcanised rubber stoppers P and Q, through which project the zinc and copper rods Zn and Cu. L and M are test tubes containing sulphate of zinc and sulphate of copper respectively, and when the cell is not in use the zinc and copper rods are placed in these tubes, each in its own solution.

The left-hand reservoir is filled with a solution of sulphate of zinc, which has a density of 1·400 at 15° Cent. This solution may be made by dissolving 555 grammes of crystals of pure sulphate of zinc in 445 grammes of distilled water. The right-hand reservoir is filled with a solution of sulphate of copper which has a density of 1·100 at 15° Cent. This solution may be made by dissolving 165 grammes of pure crystals of sulphate of copper in 835 grammes of distilled water.

The zinc and copper rods are each about 4 inches long and about ¼ inch in diameter, and they should consist of the purest materials obtainable. The zinc rod may be made from zinc which has been twice distilled, and then cast into rods of the required size. The copper rod may be conveniently obtained by electrically depositing copper on a thin wire of the same material till the required thickness is reached.

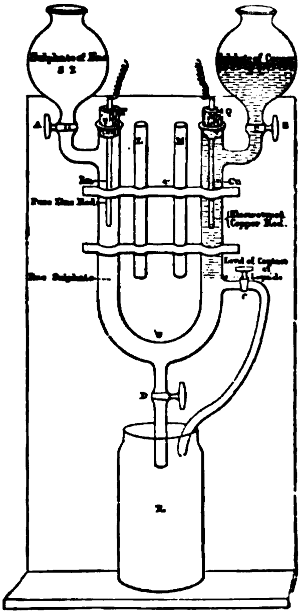


FIG. 33.—FLEMING'S STANDARD CELL.

The greatest care should be taken that the surfaces of the rods are perfectly clean before use. The zinc should not be amalgamated, but should be cleaned by rubbing with new glass-paper. The best way to insure the cleanliness of the copper rod is by depositing a fresh coat of copper on it each time it has been used; it will then present a fresh salmon-coloured surface free from spots. If any brown spots of oxide of copper are allowed to remain on its surface, the E.M.F. of the cell may be raised 2 or 3 per cent.

When the cell is required for use the

following operation has to be gone through :—

Open tap A and allow the solution of sulphate of zinc to fill the whole of the U tube; now plunge the zinc rod into the left-hand limb, as shown, and see that the stopper P is quite air-tight. Next open tap C, and allow a portion of the liquid to run off, at the same time opening tap B so that the sulphate of copper runs in to take its place in the right-hand limb. When the sulphate of zinc has fallen to the level of tap C in the right-hand tube, and the sulphate of copper has taken its place, all taps are closed, the copper rod is placed in the right-hand limb, as shown, and the cell is now ready for work.

It will be seen by this arrangement each metal is immersed in its own solution, and that the two solutions are kept from mixing.

When the solutions have been thus in contact for some time, they gradually diffuse into each other, and the line of demarcation between them becomes indistinct. On opening tap C this mixed liquid can be drawn off, and a sharp line of demarcation between the two solutions again established.

When not in use, the solutions can be run off into the waste jar R by opening the tap B.

The E.M.F. of this cell depends upon the density of the solutions; with the densities given above it is 1·072 volts, and is practically independent of any variations of temperature.

There are, however, two objections: it is difficult to make up and maintain in working order, and it is not portable. It is essentially adapted for use in a testing laboratory, and in such a situation there is no better standard.

DRY CELLS.

Since about 1893, a large number of cells, known as dry cells, have been invented. The occasion for their introduction was the need—for such work as bells, telephones, and testing—of portable sources of current less cumbersome than the ordinary wet cells. In the earlier attempts, various types of cell were produced, such as dry Daniell cells (Trouvé), but at the present time all dry batteries in commercial vogue are of the Leclanché type.

It may not be considered out of place here to remark that a dry cell in the modern sense of the term is something totally distinct from the dry pile of Zamboni. The latter consisted of a column of discs of paper or other porous material, each coated extremely thinly on one side with zinc, and on the other with copper. It thus provided a great number of surfaces of zinc and copper in contact with one another, at each of which, owing to the inevitable dampness of the air, there was the well-known contact E.M.F. Such a pile gave rise to a high E.M.F. directly proportional to the number of discs, but, owing to its high internal resistance, was incapable of delivering an appreciable current. It was capable of charging to high potentials, and at the University of Innsprück is a dry pile which has been since 1823 in continuous action, driving an electric pendulum by electrostatic attraction.

The modern dry cell is almost invariably constructed with the zinc electrode made into the shape of a pot; which serves to contain all the remaining materials. The carbon electrode usually has the depolarising mixture compressed upon it in very much the same way as that mixture is formed into blocks in the agglomerate type of Leclanché cell referred to on page 56. The depolarising material, however, in a dry cell must necessarily be in a much more porous condition than in a wet one, since otherwise the internal resistance of the cell will be undesirably high, owing to the inferior conductivity of the mixture as compared with the electrolyte.

The electrolyte consists in almost all cases of sal ammoniac, which is held in a more or less pasty medium, so as to be unspillable. The mediums variously employed include plaster of Paris, gelatine, and blotting paper, the first being by far the most common. Various additions are made to the plaster, both to secure as jelly-like a composition as possible, and to increase its conductivity. For example, a proportion of ten parts of plaster to twenty of a 10 per cent. solution of aluminium sulphate is said to give good results, the actual electrolyte being a sal ammoniac solution of one part of the salt in two of water. Occasionally sodium silicate has been employed, as have also flour, sifted sawdust, asbestos wool, cotton wool, glass wool and kieselguhr. In order to permit the gases formed when the cell is in action to escape, small openings are left at the top of the cell, which is otherwise hermetically sealed, usually with pitch, but sometimes with resin. The outside of the cell is usually protected by an envelope of card.

The internal resistance of dry cells of modern make is remarkably low, being not infrequently as low as 0·15 of an ohm, while 0·4 of an ohm is considered almost prohibitive. The open circuit voltage varies from 1·45 to 1·55 of a volt, according to the composition of the electrolyte.

Dry cells have the unenviable reputation of deteriorating when not in use, and particularly when left lying down. The probability is that in some cheaper types having an organic medium for the electrolyte, decomposition of the medium takes place with time, giving rise to an increase of internal resistance and possibly reduction of contact with the electrode from shrinkage.

CHAPTER III.—ACCUMULATORS.

THE GAS ACCUMULATOR—THE LEAD ACCUMULATOR—THE PLANTÉ ACCUMULATOR—MODERN IMPROVEMENTS—PROPERTIES OF LEAD AND ITS PRINCIPAL OXIDES—NOMENCLATURE—PASTE ACCUMULATORS—GRIDS—COMMERCIAL TYPES—PASTING THE GRIDS—FORMATION OF THE PLATES—ACID—PRECAUTIONS IN SETTING UP ACCUMULATORS—CHARGING—CHANGE IN THE ACID—DISCHARGING—CAUSES OF FAILURE—SULPHATING—BUCKLING E.P.S. CELL—THE TUDOR ACCUMULATOR—USE OF ACCUMULATORS—ACCUMULATORS AS RESERVOIRS—AS REGULATORS—LEAD PLATE ACCUMULATORS — CROMPTON-HOWELL — THE EPSTEIN ACCUMULATOR — THE CHLORIDE ACCUMULATOR—MAKING THE PASTILLES—THE LITHANODE ACCUMULATOR.

The great objections to the use of primary batteries for commercial work on a large scale are:—

(1) The initial cost of the materials which are consumed.

(2) The cost of labour and the time required to carry out the renewals.

The ordinary voltaic cell, or primary battery, is a combination of materials in which a current is generated at the expense of some substance which acts as a fuel, and which is consumed or burnt up in the process. In the case of a zinc and copper cell, if the current were forced back through it—that is to say, if it entered at the copper and left at the zinc end—it would be found that some zinc had been deposited on the zinc plate, and that the quantity thus deposited would depend upon the strength of the current and the length of time during which it flowed. The zinc thus deposited need not be of a uniform layer. For the present argument all that we require to know is that zinc in any form can be plated back by a reversal of the current.

The amount of fuel in the cell can thus be increased by the expenditure of energy in the form of a current, which is forced backwards through the cell. This is the fundamental idea of a secondary battery, or, as it is now more usually called, *an accumulator.*

A primary battery, then, is reversible, and in its reversible form it is known as an accumulator. *An accumulator may be defined as a combination of materials upon which energy is expended by the passage of an electric current, and which by that means acquires the power of generating a current on a subsequent occasion.*

THE GAS ACCUMULATOR.

If a current from a couple of cells be sent through dilute sulphuric acid by means of two platinum plates immersed in it, the liquid will be decomposed. Oxygen will be deposited upon the plate by which the current enters the liquid, and hydrogen upon the plate by which it leaves it. If the cells be now removed and the platinum plates connected through a galvanometer, it will be found that a current will flow in the opposite direction to that of the original current. This current will last only a short time, because the supply of fuel is small. The fuel consists of the hydrogen which was liberated on the platinum plate by the original current, and which now generates a current in its turn by uniting with the oxygen to re-form the original composition of the liquid. This forms a true accumulator, but its *capacity—i.e.* its power of storing up electric energy—is small, owing to the fact that only a small quantity can adhere to the plate. When the plates have become covered with their respective films of oxygen and hydrogen, the accumulator may be said to be fully charged. Any further passage of the current only liberates gases which rise through the liquid and mingle with the atmosphere. If the surface of the plate be increased, the capacity of the arrangement as an accumulator is correspondingly increased; but the plates themselves undergo no chemical change. They act solely as reservoirs for collecting and retaining the evolved gases.

THE LEAD ACCUMULATOR.

In the above described process, if pure lead plates be used instead of platinum ones, the capacity of the arrangement as an accumulator will be found to be greatly increased. The oxygen enters into chemical combination with the lead, on which it is deposited, and forms peroxide of lead —PbO_2. This peroxide of lead adheres firmly to the lead plate, and is of a reddish brown or chocolate colour. Hydrogen is deposited on the other plate, but does not enter into chemical combination with it; this plate becomes a bluish-grey colour. If the accumulator be now allowed to discharge itself, and a current be then sent through it in the opposite direction to that of the original one, it will be found that the plate which was previously coated with hydrogen will now become coated with peroxide of lead, while the surface of the one which was coated with peroxide of lead will now be reduced to the condition of *spongy lead—i.e.* lead in a finely divided condition—and will be coated with a film of hydrogen. The accumulator will now be found to have a much larger capacity than in the previous case, and can therefore supply a current for a much longer time; and it will also be found that, when it is completely discharged, the surface of both plates will be coated with sulphate of lead—$PbSO_4$. This increase in the capacity of the accumulator is due to the fact that in the first charging the oxygen bit into the lead and formed peroxide of lead; and when this peroxide was reduced by the second current to the condition of spongy lead, the plate was rendered partially porous, and a larger surface of active material was thus exposed as a fuel. When the accumulator first begins to discharge, the fuel consists of hydrogen on one plate, opposed to peroxide of lead, with a small supply of oxygen, ozone, and persulphuric acid on the other. The supply of hydrogen soon becomes exhausted, and the active material or fuel then consists of pure spongy lead. During the first portion of the discharge, the E.M.F. of the combination varies between 2·1 and 2·5 volts; but as soon as the supply of gases is exhausted, the E.M.F. falls to about 2 volts, which may be considered to be the normal E.M.F. of the ordinary lead accumulator.

The E.M.F. remains practically at this value until the cell is nearly discharged, when it begins to fall very rapidly.

THE PLANTÉ ACCUMULATOR.

Planté constructed his accumulator as follows. He took two sheets of lead, each of which had a projecting lug to serve as a terminal, and, having placed one upon the other, separating them by two india-rubber bands which prevented them from touching, he rolled them into the form of a cylinder, which was held in position by an ebonite cross at the top. These two stages are illustrated in Fig. 34.

The cylinder he placed in a glass vessel, containing dilute sulphuric acid—1 of acid to 10 of water.

The accumulator was now ready for forming ("forming" is the technical name for the process of coating one plate with peroxide of lead and the other with spongy lead). Planté now sent a current from a couple of Bunsen cells through the arrangement by means of the two projecting lead lugs, till one plate became coated with peroxide of lead and the other with hydrogen. This condition can be recognised by the gases evolved by the decomposition of the water arising through the liquid in bubbles. The accumulator was now allowed to rest for about fifteen minutes, when it was discharged and a current sent through it in the opposite direction till the bubbles again began to come off. It was again allowed to rest, but for a longer time than before, and again discharged. These operations were continued over several months, till the capacity of the accumulator—which was continually increasing, owing to the plates being bitten into more and more at each succeeding charging—had become sufficiently large for practical purposes.

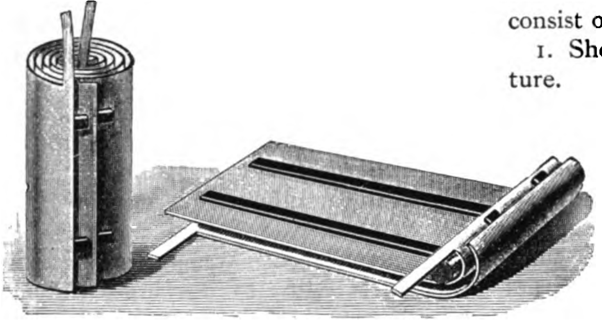


FIG. 34.—PLANTÉ'S ORIGINAL ACCUMULATOR.

In its completed form one plate has become entirely honeycombed, and consists to a great extent of pure spongy lead, while the other has been partially turned into peroxide. The ultimate fate of a Planté accumulator most usually is that it disintegrates and falls to pieces at the slightest shock at the very time when it is working at its best, and when its storage capacity is at a maximum.

MODERN IMPROVEMENTS.

The principal improvements which have been made in the modern accumulator consist of the following features:—

1. Shortening the process of manuture.

2. Bringing the active materials into contact with conductors which are not seriously attacked by the action of the cell, and which thus prolong its life.

3. Improved methods of separating, supporting, and connecting the plates, and providing proper circulation of the liquid.

As far as theory is concerned the modern accumulator differs but slightly, if at all, from that of Planté.

CHEMICAL CHANGES IN THE ACCUMULATOR.

The chemical theory of the lead accumulator has been the field of a long-fought battle, in which many contestants have found scope for action. Indeed, several points still remain imperfectly disposed of, but the solution of the main issue must be credited to Messrs. Gladstone and Tribe, who advanced their double-sulphation theory in 1882-3. Taking actual analyses of the active material at both electrodes, they demonstrated conclusively that the spongy lead at the negative, and the peroxide at the positive, were both converted into lead sulphate by the discharge current. Formerly the formation of sulphate under any conditions was regarded as the bane of every accumulator, the action at the positive being considered to be a reduction from peroxide (PbO_2) to monoxide (PbO) which last, in the presence of sulphuric acid, tended as a secondary reaction to become sulphated. The activity at the negative, as evidenced by the voltage at that surface, was unexplained, although Dr. Lodge suggested that it was due to occluded hydrogen. Gladstone and Tribe's theory, supported as it was by experimental data, held a very strong position which has steadily improved, although it rendered the physics of the cell even more difficult to understand than before. The main difficulty lies in the fact that lead sulphate, as ordinarily prepared, is white, non-conducting, and insoluble; whereas in a healthy accumulator, the eye cannot detect any white substance in the active materials, and moreover, the lead sulphate if produced, must be both soluble and a conductor, otherwise a charging current could not re-convert it to Pb and PbO_2 respectively.

The opponents of the double-sulphation theory admit direct sulphation at the negative, but maintain that the direct production of sulphate at the positive is contrary to the principles of true electrolysis, and that it is necessary to produce directly at the positive something different from that at the negative. This something different must clearly be a lower oxide; according to Darrieus, it is PbO, while according to FitzGerald it is Pb_2O_3. A most ingenious theory was advanced by Wade in 1900, according to which an explanation of the physical difficulties above referred to might be found in regarding the material, which analysis showed to be lead sulphate, as an allotropic modification of the normal lead sulphate of the chemist. This would at once account for the non-appearance of any white substance, and for the ready reconversion of the discharged material into lead and lead peroxide. The appearance of white lead sulphate in unhealthy cells, known to occur when cells are allowed to stand discharged, he explained as a molecular change, needing time, from the allotropic modification to the chemists' normal sulphate. This explanation, although delightfully simple, and strongly supported by the known peculiar behaviour of lead in various combinations, has met with considerable opposition. The most pertinent adverse criticism appears to be that founded on the well-known fact that highly oxidised products, such as H_2O_2, and persulphuric acid, are produced in the cell, and that these may account for the difficulties without introducing a new complication such as Mr. Wade suggests.

Apart from the divergence of views as to the process, all authorities appear to concur in the view that the ultimate product at both electrodes is $PbSO_4$, so that the following equation may be taken to represent the final changes:—

$$PbO_2 + 2\,H_2SO_4 + Pb \mathrel{\substack{\xleftarrow{\text{(Charge)}} \\ \xrightarrow[\text{(Discharge)}]{}}} 2PbSO_4 + 2H_2O.$$

As regards intermediate stages, supporters of the double-sulphation theory give the following as the discharge reactions:—

At the negative:—

$$Pb + H_2SO_4 = PbSO_4 + H_2.$$

At the positive:—

$$PbO_2 + H_2SO_4 = PbSO_4 + H_2O + O.$$

And, further, that the H_2 and O liberated as thus indicated combine to form a second molecule of water.

These reactions are the source of the E.M.F.s, all tending in the same direction, and the magnitudes of those at the electrodes depend upon the strength of the acid and upon the state of the active material. Apart from these variations their magnitudes may be set down as of the following approximate values:—

At the negative	...	0·2 volt.
At the positive	...	0·3 „
Formation of H_2O	...	1·5 „
		2·0 volts

DIFFUSION OF ELECTROLYTE.

When it is appeciated that on discharge two molecules of water are liberated for every two SO_4 ions abstracted from the electrolyte, it will be recognised that a local weakening of the acid is taking place at the electrode surfaces. This weakening varies in rapidity with the current strength since, as we have seen, all chemical changes are proportional to the product of current and time. If the current is to be maintained, the local weakening of the acid must be made good by bringing in fresh supplies. This will take place by diffusion, owing to the difference in densities of the weak and strong solutions, and the stronger acid from the bulk of the electrolyte will flow in. If heavy currents are to be taken, full liberty must be left to the electrolyte to diffuse by spacing the plates widely and by leaving space between their edges and the walls of the containing box.

Nor is the necessity for this freedom felt only outside the electrodes. The chemical changes penetrate to some small depth below the surface, indeed the whole of the active materials (PbO_2 and spongy Pb) which form a skin or envelope, must be involved. Hence the need of producing great porosity in the formation of the active materials, especially where high discharge rates are wanted.

DISCHARGE VOLTAGE.

The whole E.M.F. of the accumulator is not available at the terminals owing to the internal resistance, but the terminal voltage of the cell falls as discharge proceeds. The general shape of the discharge voltage curve is shown in Fig. 43. The diminution of terminal voltage is attributable to two distinct causes—(*a*) decrease of the true E.M.F.; (*b*) increase of the internal resistance.

The first of these is not great, and is due chiefly to the gradual weakening of the electrolyte. The initial (charged) density of the electrolyte is usually about 1·2, corresponding to 27·32 per cent. H_2SO_4, and it may fall to about 1·15 or even 1·12. The change of density from 1·2 to 1·15 occasions a change of 0·041 volt, in true E.M.F., a very small matter. For reasons which are referred to below, the terminal voltage may be allowed to fall to 1·8, so that it is clear that the drop is but little attributable to fall in true E.M.F. On the other hand the internal resistance of the active material (or at least of the electrodes) has been shown by Haagn to rise easily to a value, at the end of discharge, double or even two and a-half times as great as at the commencement (*see* Fig. 35). He also showed that it is virtually independent of current strength.

DISCHARGE RATE.

The number of ampere hours theoretically obtainable from an accumulator is simply proportional to the weight of active material available, just as in a primary cell. In point of fact, however, it is not possible under the most favourable conditions to bring the whole weight of PbO_2 and spongy Pb that have been formed, into an available condition. The reasons for this are disputed, and lack of space forbids our entering further into this point. Quite apart from this fact, however, the proportion of formed material which is actually available and active is only so in a variable degree, and this variation depends upon the *rate* of discharge. In all probability the cause is the weakening of acid in the pores, since a cell discharged rapidly down to 1·8 volts and then allowed to stand will rise again to 2 volts, and can be further discharged before it again falls to 1·8 volts. The period of rest allows the depleted acid to be replaced by diffusion.

The chief criterion of discharged condition is the voltage, which must not be less (*while discharging*) than 1·8, or, if the rate be so high as to reach that value in one hour, it may be further continued till 1·75 volts is reached

In Fig. 35 are given three curves. The upper one shows the variation of capacity in an accumulator discharged at rates ranging from about 1 ampere to 40, the discharge being completed in from 90 hours down to as little as one hour. The two lower curves show the changes in internal resistance which occur during charge and discharge at the five-hour rate.

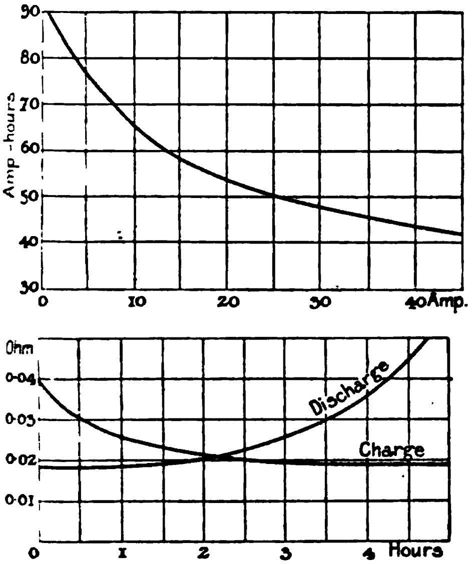


FIG. 35.—CURVES SHOWING CHARGES IN CAPACITY AND RESISTANCE.

DISCHARGE CRITERIA.

Since the well-being of an accumulator is so greatly affected by the treatment it receives, or in other words, whether or no it is overcharged or overdischarged, it becomes a matter of the first importance to establish proper criteria of the charged and discharged conditions. Unfortunately no one simple test can be applied to show whether a cell is charged or whether it is discharged, and it becomes necessary to have reference to two or three points, one of which alone would be insufficient to determine whether the cell is charged or not. There are in all four indications of the state of a cell, namely: (*a*) voltage while the current is passing, (*b*) density of the electrolyte, (*c*) the production of gas in the electrolyte, (*d*) the colour of the plates.

The first of these indications is perhaps at once the most readily observed, and the most significant; but the importance is not always sufficiently realised of making the voltage test *while current is passing*. A reference to Figs. 41 and 42 on pages 78 and 79 will show how the voltage of the accumulator rises and falls respectively during the passage of a charging or of a discharging current. It must, however, be carefully remembered, and the point cannot be too strongly insisted upon, that if the current be stopped at any point, even after the most exhaustive discharge, and the cell be allowed to rest, the terminal voltage after the lapse of an hour or so, will be two volts, if tested by a modern high resistance voltmeter. Should, however, a current be taken from the cell so exhausted, the terminal voltage will at once fall virtually to zero, within a few minutes at the most. On the other hand, if the cell were in a fully charged condition, the voltage on discharge would not fall appreciably, or if a charging current were passed, would rise with great rapidity to 2·5, and eventually to 2·7 volts.

It has already been pointed out that during the period of discharge, two molecules of water are formed for each molecule of lead sulphate at one pole. The liberation of this water with the accompanying transfer of the SO_4 ions to the electrodes clearly results in a weakening of the electrolyte, and an accompanying change in its specific gravity. In a modern accumulator the amount of available acid is always considerably in excess of the available active material on the electrodes, so that the limit to the reaction is placed by the condition of the electrodes rather than by the condition of the electrolyte. The total range of change of density in a modern accumulator does not ordinarily exceed ·015, and is sometimes less, working values being of the order of 1·190 for the lower limit and 1·200 for the upper limit. It will be realised therefore that if this change is to afford any indication, specially constructed hydrometers of great sensitiveness must be employed. Several such are illustrated in Fig. 39 on page 75. Within the range of its alteration, the change in density of the electrolyte may be taken as roughly proportional to the quantity of electricity which has passed through the cell in one direction or the other.

In order to obtain the full value of these indications in practice, it is, of course, important that all the cells in a battery should, when fully charged, have electrolyte of the same density. Some little difficulty arises occasionally in this connection owing to the inevitable variations in manufacture. In consequence of these, a battery of cells may be filled with acid of one density at the time of erection, but even after allowing some weeks of regular working to eliminate inequalities as much as possible, a small percentage of the cells will be sure to have electrolyte either too dense or too weak as compared with the rest. It is therefore advisable to correct these inequalities by the careful addition of water or of acid, as the case may require, so that within, say, a month or six weeks after their first erection, the electrolyte in all the cells will stand at the same density when the cells are fully charged.

When all the active material is fully converted into peroxide and pure lead at the respective electrodes, a continuance of the charging current can effect no further chemical change in the electrodes, and the electrolysis is now limited to the water of the electrolyte, which is broken up into hydrogen and oxygen. These gases are thus under such conditions liberated in considerable quantity, and pass up through the liquid, to which they give the appearance of boiling, and when this occurs the cells are said to *gas*, or to *boil.* The occurrence of gassing, hence, indicates a complete transformation of all the active material in the electrodes, provided only that the charging current is not too great. With too great a current, gassing will often occur before this point has been reached.

The final criterion is that of colour. This to the unpractised eye is somewhat difficult of application. The negatives should be of a clear slate colour, perfectly uniform over the whole surface, and having a crystalline appearance. The positives should be of a rich brown, to which chocolate is the nearest approach. If the colour is almost black, it indicates that the cells have been systematically overcharged, while anything in the nature of a reddish tone to the brown indicates insufficient charging, and a dangerous state of affairs which requires immediate rectification.

The criteria may thus be summarised as follows: A cell is fully charged when (1) the voltage has remained steady with the normal charging current for at least half an hour; and (2) the density has ceased to rise under the same conditions; and (3) the cell is gassing freely with normal charging current. A cell must be considered discharged if the voltage has fallen to 1·8 with not less than normal discharge current.

VARIATION OF CAPACITY.

From what has already been said in reference to the circulation of the electrolyte, porosity of the active material, and change of internal resistance, it will be readily understood that a high discharge rate may cause so rapid a reduction of active material at the surface of an electrode, that the acid in the pores becomes entirely used up, and the inner portions of the active material cannot be made use of until fresh acid has diffused through the mass. There thus exists a kind of rivalry between the rate of depletion and the rate of diffusion of the acid, the former being governed of course by the current strength, *i.e.* discharge rate. As a consequence, a rapid discharge rate causes a fall of voltage before the whole of the active material is properly sulphated, and a cell may be discharged rapidly to the voltage limit, allowed to stand and recoup itself by diffusion of acid, when a further discharge may be taken from it before the voltage limit is again reached. It is customary, therefore, to express the capacity of a cell with reference to the discharge rate, and the general relationship between discharge rate and capacity is shown in the upper diagram of Fig. 35, while the lower diagram shows the change in internal resistance as charge and discharge proceed.

PASTED PLATES.

Owing to the tedious nature of the Planté formation, Faure, in 1881, suggested using what may be called a chemical half-way house, and instead of starting with pure lead for both electrodes, to use red lead, which may be represented by the formula, Pb_3O_4 on the positive plate, and litharge, PbO, on the negative. These materials were to be prepared in the form of a paste, which was then to be pressed into the interstices of a leaden framework or grid. By this means the forming of the active material consisted in further oxidising the Pb_3O_4 to PbO_2 and in reducing at the same time the litharge to pure lead. This method at once sprang into great favour, not only on account of the rapidity of formation, but because it enabled great thicknesses of active material to be produced, and for a long time Planté-formed plates were looked upon as an unnecessarily expensive luxury. Continued experience, however, led manufacturers and users to the conclusion that the mere presence of a large mass of active material was by no means the only essential to a good accumulator, but that there must also be good cohesion between the particles forming the mass, and especially must there be excellent contact and even adhesion between the active material and the supporting grid. Failure to attain these desiderata resulted in a host of troubles, among which were the falling of pellets of paste from the grids, or looseness of contact between the paste and the grids. The result of active material dropping out was not only to reduce the capacity of a plate by the loss of so much active material, but not infrequently a pellet would bridge the gap between two adjacent plates, so causing an internal short circuit, with ruinous results. Looseness of contact prevented the active material concerned from taking its full share of current, so that it tended to become imperfectly oxidised or reduced, and ultimately sulphated into white sulphate. Current would then begin to attack the supporting grid, which would in time become eaten through. In modern

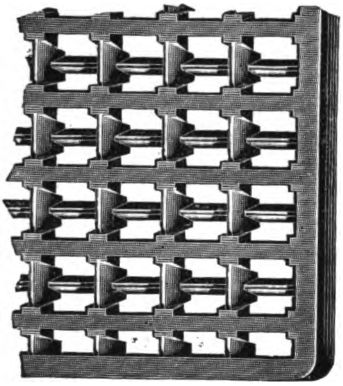


FIG. 36.—ENLARGED SECTION OF NEGATIVE GRID, SHOWING THE DESIGN ADOPTED TO KEY IN THE ACTIVE MATERIAL ON BOTH SIDES.

accumulators the utmost care is exercised to avoid these evils when pasted plates are used, by designing complex grids which hold the paste very securely. One type of grid is illustrated in Fig. 36.

PASTING THE GRIDS.

The filling of the grids with paste is an operation which can be performed *in a manner* by a person of very limited electrical knowledge, but the best method of doing it is a carefully guarded trade secret of each of the companies. The main outlines of the process are as follows.

For the brown plates, take as much red lead as will make enough paste for a single plate and mix it with sulphuric acid diluted with eight times its volume of water. Mix in a wooden bowl, adding sufficient to form a soft paste, which should be immediately spread over the grid with a wooden spatula, the superfluous paste being carefully scraped off before it hardens. This operation should be performed as quickly as possible; any delay is ruinous to the plate. The reason why no time should be lost appears to be that the addition of the sulphuric acid (H_2SO_4) converts the red lead (Pb_3O_4) into sulphate of lead and peroxide of lead, and this conversion should not be completed before the paste has been placed in the position which it is ultimately required to occupy. The reaction which takes place in this process may be chemically expressed thus :

$$\underset{\text{Red lead}}{Pb_3O_4} + \underset{\substack{\text{Sulphuric}\\\text{acid}}}{2H_2SO_4} = \underset{\substack{\text{Peroxide of}\\\text{lead}}}{PbO_2} + \underset{\substack{\text{Sulphate of}\\\text{lead}}}{2PbSO_4} + \underset{\text{Water}}{2H_2O}$$

Both peroxide of lead and sulphate of lead are insoluble in sulphuric acid.

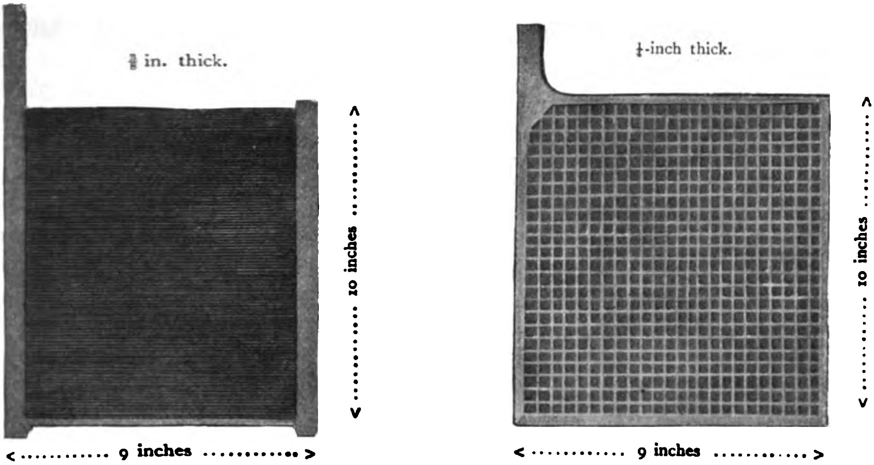
The plate is then placed to dry for about twenty-four hours at a moderate temperature. When the operation has been properly carrried out the paste ought to consist of a hard solid mass adhering firmly to the grid.

The pasting of the grey plates differs from the above only in the different materials used. Litharge is employed instead of red lead, and a weaker acid—1 part in 20 of water—is used.

QUICK PLANTÉ FORMATION.

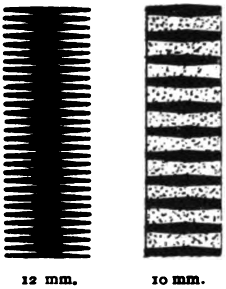
A device having for its object the shortening of the Planté formation is the employment of nitrates or nitrites of potassium or sodium in the forming electrolyte. This greatly accelerates the attack on the positive plate owing to the presence of nitrogen acids which are formed in the electrolyte. It is, however, of prime importance that these shall be perfectly eliminated from the plates before they leave the factory, as their presence in the cell under working conditions would cause the backbone of the plate to be rapidly eaten away.

This is effected by finishing them off very carefully in successive baths of pure electrolyte, using high current densities. The use of a high current density causes the production on the surface of the positive lead support of a gelatinous film of what appears to be hydrated lead peroxide in a colloidal form. This was observed by Planté in his early experiments on the surface of the lead strip that he used. In such a position it rapidly changes into lead sulphate by local action with the lead support, the film itself serving to transmit sufficient moisture to maintain the action. When, however, it is buried underneath a layer of active material, the latter prevents free access of the electrolyte to this film, which therefore acts as a protection to the lead support from attack by sulphation. The formation of this film between the active material and the lead support is known as "sealing off," and must be the end of every Planté process, whether the original slow one or a modern quick one. Every battery, moreover, should be slightly overcharged once a fortnight when in


⅜ in. thick.
10 inches
< .... 9 inches .... >
¼-inch thick.
10 inches
< .... 9 inches .... >

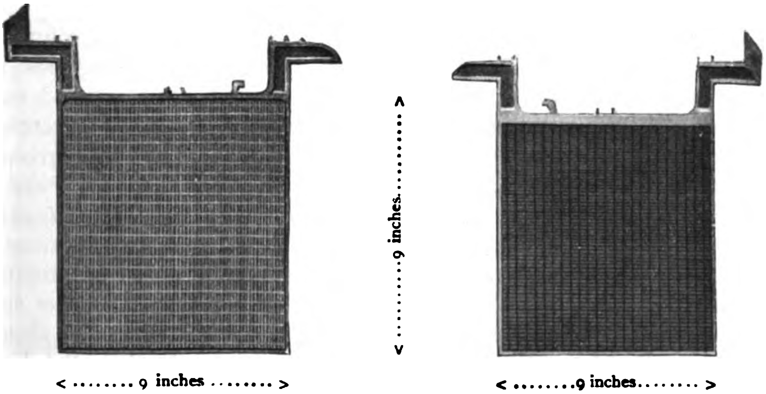
STRIP POSITIVE.
Weight, 9½ lbs.

PASTED NEGATIVE.
Weight, 5 lbs.



SECTION OF POSITIVE PLATE.

SECTION OF NEGATIVE PLATE.



PLANTÉ FORMED POSITIVE.
Weight, 13½-lbs.

NEGATIVE PLATE.
Weight, 9-lbs.

FIG. 37.—REPRESENTATIVE PLATES; "PASTED" AND "FORMED."

regular use, and also when standing idle, so as to preserve or renew, if necessary, this sealing-off film.

Representative types of grid and plate are shown in Figs. 36 and 37.

An interesting construction of positive plate is shown in the upper portion of Fig. 37. The plate consists of a number of horizontal strips of lead tape, the ends of which are consolidated into two vertical lead bars. The tape lies with its width in the horizontal plane, so that any expansion which may take place causes the tape to buckle in a vertical direction. This buckling is of course perfectly harmless, since it does not tend to short circuit the plate on to a neighbouring negative. The negative for use with this positive is shown to the right of it, and is of the pasted type. The grid used is that shown in Fig. 36. This type of cell is made by the D. P. Batttery Company only.

In Fig. 37 is also shown a typical pair of plates, the positive being Planté formed by a quick process and the negative pasted. It is now common practice to use pasted negatives with formed positives.

FORMATION OF THE PLATES.

This operation is the same for both kinds of plates. To form the brown plates, a number are placed in a shallow bath, and all connected together. In this form they are used as an anode, the kathode being formed by any convenient conductor, usually some old grids. When all is ready acid of strength 1 to 4 is run into the bath and the current immediately started. The current must be kept on continuously for about twenty hours, at the end of which time the plates will have become fully formed and have attained their usual brown colour. The terminals of these plates are always painted red, while those of the grey plates are usually painted black. This custom is extremely convenient when coupling up a battery, and is universal.

The formation of the grey plates is a more tedious operation. They are placed in a bath so as to form the kathode, the solution being sulphuric acid diluted with about twenty times its volume of water. A much weaker current is used for forming than is the case with the brown plates, and the process takes about a week to perform. Any increase of current only evolves hydrogen from the liquid, and the process of formation is not hastened.

ACID.

The quality used both in the construction and maintenance of accumulators is of importance. The common commercial acid made from iron pyrites contains arsenic as an impurity, and should not be used when pure acid made from native sulphur can be obtained. The acid used in accumulators is always diluted with a considerable quantity of water. The useful range for acid in paste accumulators lies between a solution containing 15 per cent. of acid to 85 per cent of water, and 27 per cent. of acid to 73 per cent. of water, the density of the first solution being 1·106, and the density of the second solution being 1·198.

The conductivity of a solution of sulphuric acid in water depends upon the density of the solution, and varies in a curious manner upon the percentage of acid in solution. The curve given in Fig. 38 (taken from Professor Pickering's investigations, *Philosophical Magazine*, Fig. 18, May, 1890) shows the manner in which the conductivity rises and attains a maximum at about 25 per cent. of acid ; then it decreases to a density of about 85 per cent., when it again rises slightly, and falls finally to a minimum value.

Although a slightly greater E.M.F. would be obtained by using acid of greater strength than is general, the practice cannot be followed because of the greater risk of attack of the active materials when the cells are standing idle. Especially must this be avoided with pasted plates to prevent attack of the grids. It should be mentioned that grids are often stiffened, particularly in cells for automobile work, by adding antimony to the lead from which they are cast.

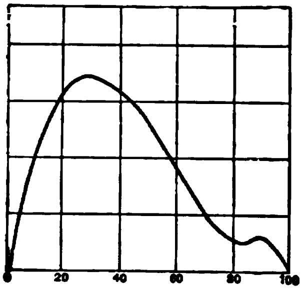


FIG. 38.—VARIATION OF CONDUCTIVITY OF SULPHURIC ACID OF VARYING DENSITY.

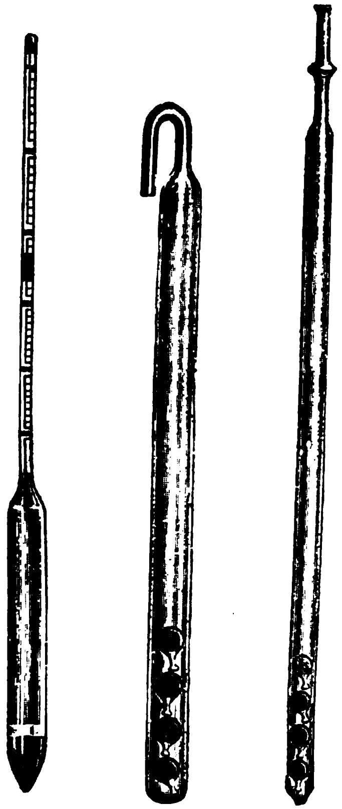
The usual form of hydrometer is shown at *a* in Fig. 39; a dark band on the stem shows the usual range of change in density. The bulb is flattened to allow of its insertion and free floating. In the other two forms (*b* and *c*), specific gravity beads are used, four in number and differently coloured. The beads float at the respective densities of 1·150, 1·170, 1·190, and 1·200. The containing tube is perforated at the bottom, and for cells in glass boxes hangs on the side of the glass box. For cells in closed or open opaque-sided boxes the form shown at *c* is used. The instrument is immersed, and the top opening then closed with the finger; the hydrometer is then withdrawn containing a sample of the liquid. The bead floating near the middle of the tube indicates the density.

PRECAUTIONS IN SETTING UP ACCUMULATORS.

For stationary cells up to fifteen plates or so, the containing boxes are of glass. For larger sizes, and for ship or automobile work, they are of wood, lead lined.

The plates are assembled with one more negative than the number of positives, so as to utilise both sides of every positive. Connection from cell to cell is made by bolting the lead lugs together, or preferably by "burning" them, *i.e.* fusing them with a blow pipe. If bolts are used they are of brass, and the lugs must be scraped bright and vaselined before being bolted together. Vaseline must also be freely applied to the bolts to protect them from acid.

Sheets of glass are laid on top of the cells to check loss of acid by the spraying which occurs when they are gassing freely. These may be seen in Fig. 43, and so also may both bolted and burned types of connections referred to above.



(*a*) (*b*) (*c*)

FIG. 39.—ACCUMULATOR HYDROMETERS.

The level of the acid gradually becomes lower owing to evaporation, and should be rectified by the addition of pure water, since it is the water alone that evaporates, not the acid. During charging, a certain amount of spray is given off when the cell is nearly charged, which spray carries off some acid with it; in consequence the density of the solution falls, and it is necessary to add some acid to the solution. Pure acid should on no account be added to the cell, but should be added only when diluted with water. The resistance of the acids used in accumulators decreases as the density increases, while if acid through any cause becomes very dilute the resistance of the accumalator rises very considerably.

The variation of density should be kept as small as possible, and, in order to ensure that this should be so, there must be plenty of acid present in the cell and plenty of room for its proper circulation.

It is of the utmost importance that the water used to make good evaporation, for "topping up," as it is called, should be absolutely pure, free from iron, lime, or magnesium. Failing distilled water, carefully collected rain water may be used, or where this is not available, well boiled and decanted spring water. Topping up should be resorted to directly the level of the liquid falls to within a quarter of an inch of the top of the plates. The level should be kept at half an inch above the plates, and the cells regularly inspected to ensure this.

Each cell should be placed on a wooden tray or on two pieces of wood, which in their turn are each supported by two oil insulators similar to the one illustrated in Fig. 40. The upper figure shows a perspective view of the insulator, while the lower is its section showing the oil.

EFFICIENCY OF ACCUMULATORS.

Under ordinary usage accumulators need about 12 per cent. more ampere hours' charge than the previous discharge, and at the same time the voltage of charge is greater than that of discharge. The result is that the ampere-hour efficiency does not exceed 90 per cent., while the energy, or watt hour, efficiency is of the order of 70 per cent. Very careful working may attain 75 per cent., but this must be regarded as exceptional. Under the conditions which obtain with reversible boosters, as described in a later section of this book, much higher efficiencies might be obtained when charge and discharge alternate with great rapidity, since the difference in internal resistance and in voltage is not so great.

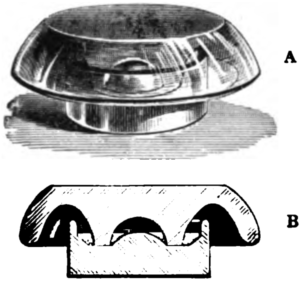


FIG. 40.—ACCUMULATOR INSULATOR: (A) IN PERSPECTIVE, (B) IN SECTION.

It was formerly the custom to have the plates as close together as possible so as to decrease the external resistance; but experience has proved this to be a mistake. In the modern types of accumulators the distance between the plates has been increased to about three-eighths of an inch, and in some cases the distance is increased to as much as half an inch, the distance being maintained by means of the lead bands connecting the plates, and by glass tubes which are placed vertically between every positive and negative in two or more rows. They may be clearly seen in Figs. 43 and 46. The plates also hang clear of the bottom by some three or four inches. It follows that :—

(*a*) There is less chance of short circuiting by pieces of paste or other materials falling between the plates.

(*b*) There is more space for the circulation of the acid, which consequently varies less in density.

(*c*) The resistance from plate to plate is more evenly distributed, the current density is more uniform over the whole surface, and there is therefore less tendency on the parts of the plates to buckle.

(*d*) The difference between the resistance of the paste pellet and the exposed grid becomes relatively inappreciable compared with the total resistance from plate to plate.

CHARGING.

When a number of accumulators have been received from the manufacturers, no time should be lost before setting them up *in series* and starting charging. The strength of acid to be used depends upon the condition of the plates as already described; the more completely they have already been charged the stronger must be the acid. The strength of current to be used for charging depends upon the number of plates in each cell and their size. A good rule is to allow 2·5 amperes for every square foot of surface on the brown plates, both sides of the plates being taken into account as active surface. The E.M.F. of each accumulator may be taken at 2 volts, but during the operation of charging it rises as high as 2·3, and higher when the accumulator is nearly fully charged. The consequence is that the dynamo has not only to drive a current through the resistance of the circuit, but has also to overcome the back E.M.F. of the accumulators, this back E.M.F. being equal to the number of accumulators in series multiplied by about 2¼. In order, then, to keep the charging current constant, means must be provided for regulating the E.M.F. of the dynamo. When charging is first started the E.M.F. of the accumulators is at its lowest, and care must be taken that the current sent through them is not too strong. As charging proceeds, the E.M.F. of the accumulators rises; when charging is nearly completed it rises somewhat abruptly.

Fig. 41 shows the charging terminal E.M.F. of an Epstein accumulator.

DISCHARGING.

The strength of current which should be used either in charging or discharging an accumulator depends entirely upon the number and size of the plates; in other words, upon the area of active material upon which chemical action can take place. The E.M.F. of an accumulator containing a single pair of plates is exactly the same as that of one containing a large number; but its internal resistance is considerably greater, being proportional to the amount of plate surface immersed in the liquid. The normal current with which an accumulator should be charged is the same as would discharge it in ten hours. This rate may be exceeded if necessary, but it should never rise more than 25 per cent.

When a sudden large discharge is taken gases are often evolved from the plates with sufficient force to drive portions of the paste out of the grids, and thus to reduce the capacity of the accumulator by reducing the amount of active material in it. This is notably the case if *sparking* is resorted to when it is desired to ascertain whether a particular cell is charged. By "sparking" is meant taking a short piece of wire, laying it for an instant directly across the terminals of the accumulator, and seeing if a good spark is obtained on breaking the circuit. This is a most ignorant and injurious practice. It simply amounts to short circuiting the accumulator, and causing a sudden and enormous current to circulate while the wire remains in contact. This large current gives rise to a sudden evolution of gas in great quantities—resembling an explosion on a small scale — in the substance of the plates, and the probable expulsion of a

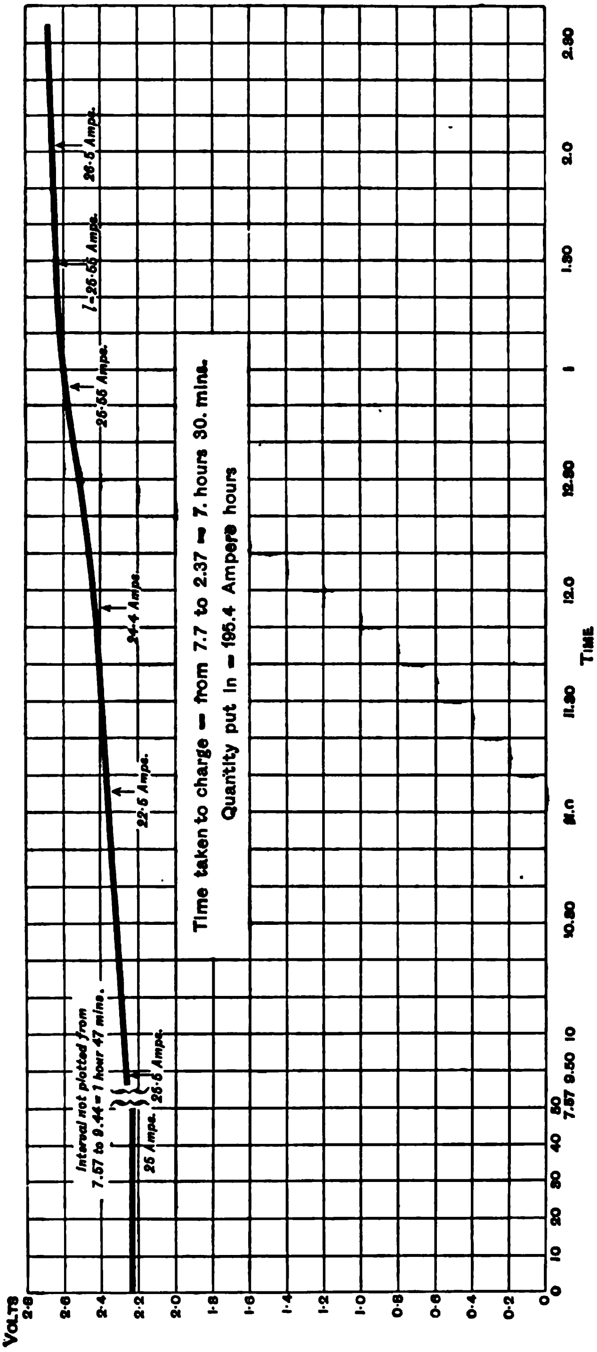


FIG. 41.—RISE OF VOLTAGE OF ACCUMULATOR DURING CHARGE AT CONSTANT CURRENT.

portion of the paste in company with the gas. A piece of paste thus expelled may be sufficiently large to bridge over the space separating a pair of plates and thus to short circuit the accumulator.

These remarks do not apply with equal force to the Planté or any accumulator containing plates of ordinary sheet lead. As they contain no paste, their capacity cannot be reduced by a sudden large discharge, but any want of symmetry between the plates is increased, and a tendency to buckling is soon developed. An accumulator made of sheet lead has a smaller capacity than one containing paste, but it is less liable to injury when large discharges are taken. The capacity of an accumulator is stated in terms of the number of ampere hours it can store up, an ampere-hour meaning a current of one ampere lasting for one hour. (It does not mean that the accumulator must be discharged at the rate of one ampere an hour.) An ampere hour is equally well represented by twelve amperes flowing for five minutes, or by sixty amperes flowing for one minute.

An accumulator should never be discharged beyond the point where its E.M.F. begins to drop rapidly.

Fig. 42 shows the variation in the terminal E.M.F. of an Epstein accumulator when discharged below the point where the E.M.F. falls suddenly. The rate of discharge was 50 amperes; the total time was two hours nineteen minutes, and the readings were taken every minute during that time. For the last ten minutes it was found impossible to maintain the current at 50 amperes, no matter how quickly the external resistance was varied.

CAUSES OF FAILURE.

Every accumulator in a set ought to begin to gas at about the same time if they are in good condition. If one begins to boil before its time, its capacity has through some cause become reduced; while, on the other hand, if any one shows no tendency to boil, it is probably short circuited. The capacity of an accumulator becomes reduced by the formation of an insoluble sulphate on the brown plate, which, if not attended to in time, will probably result in its destruction.

The sulphating may be caused by having the acid too strong, by discharging below the point where the E.M.F. falls rapidly, or by leaving it uncharged for a length of time.

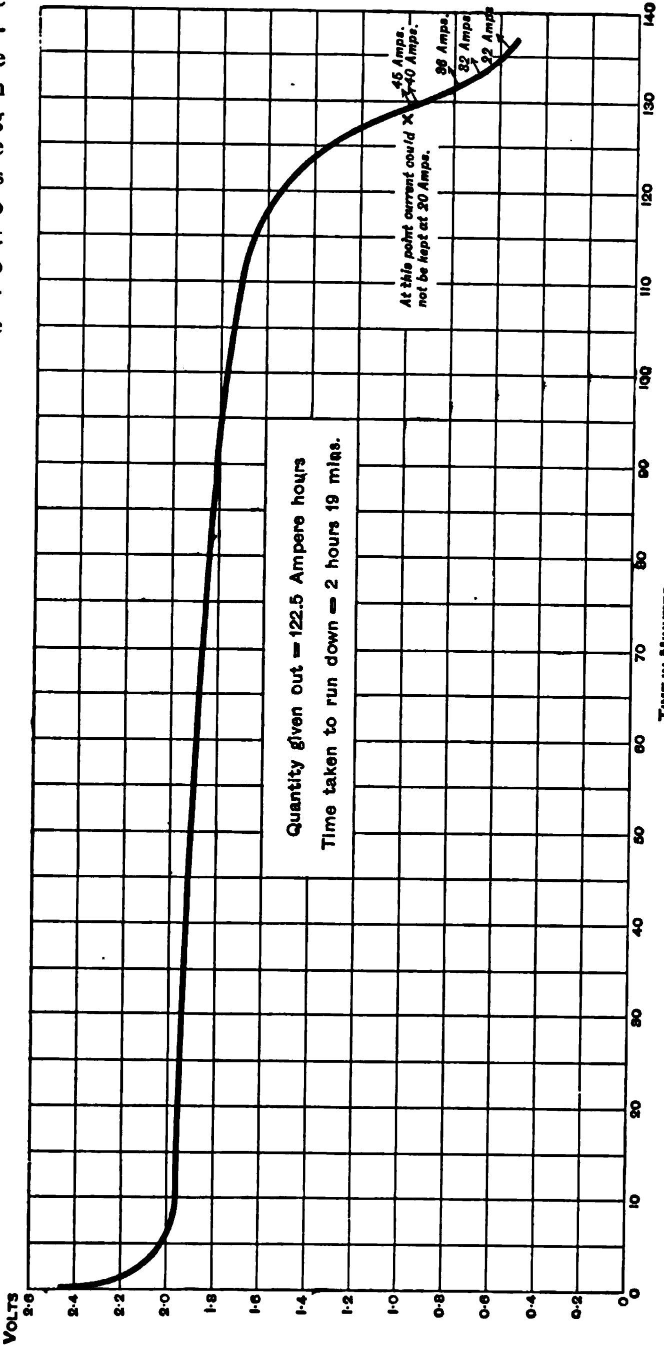


FIG. 42.—VARIATION IN VOLTAGE OF AN ACCUMULATOR WHEN DISCHARGED AT CONSTANT CURRENT.

The short circuiting may be caused by the *buckling* of the brown plate till it touches the grey, by a piece of paste getting loose and falling between the plates, by some piece of conducting substance falling into the cell and connecting the plates, or by want of proper insulation, which discharges the accumulator by leakage.

The short circuiting may be the consequence of sulphating of the plates, and short circuiting itself invariably causes sulphating. If a cell is found to be suffering from one of these defects, it should at once be cut out of the circuit and the evil remedied. Any delay injures the accumulator, and may result in its destruction. When the evil has been remedied, it should be replaced in the circuit during charging and cut out while the others are being discharged. It should not be discharged until found to boil at the same time as the others.

An accumulator should never be allowed to stand discharged for any length of time, but should be re-charged as soon as may be after the completion of a discharge. A series of partial discharges, however, may be taken in succession from a cell, but when once a charge has been commenced, it should be carried to completion before allowing any discharge whatever to take place.

SULPHATING.

If an accumulator is completely discharged, all the paste on the brown plate will consist of sulphate of lead ($PbSO_4$), and the liquid will be in its most dilute condition. If it is allowed to remain in this state without charging, the brown plate will be converted into the allotropic insoluble form, which offers a high resistance and is not easily decomposed by a current. The formation of this substance is what is usually referred to as "sulphating" in an accumulator, and it must not be confounded with the healthy formation of sulphate of lead on the electrodes. Wherever the term "sulphating" is here used it is the formation of the insoluble form of sulphate that is referred to, and this substance is the cause of most of all the trouble that an installation of accumulators can give.

Sulphating is due to one of the following causes:—

(*a*) Discharging the accumulator beyond the point where the E.M.F. begins to fall rapidly.

(*b*) Allowing the acid solution to become too weak.

With ordinary care the second of these causes ought never to arise; it simply points to gross carelessness in not attending to the indications of the hydrometer. The acid may be too weak either through the original solution having been too weak or through some of the acid having been carried off in the spray when the accumulator was gassing, and its place taken by the water which was poured in to keep the level of the liquid constant. On no account should the liquid be allowed to fall so low as to expose any portion of the plates to the action of the atmosphere.

The other and more usual causes of sulphating may arise through one of the following reasons:—

1. Wilfully discharging beyond the point where the E.M.F. begins to fall rapidly.
2. Short circuiting.
3. Allowing the accumulators to remain unused for a considerable length of time.

The first of these reasons can always be avoided by testing each accumulator with the voltmeter described in the last section, or some similar instrument which will give an indication of the E.M.F.; or by an intelligent observation of the hydrometer when the strength of the acid is known to be correct.

Short circuiting may be caused by an accidental short circuit on the main leads or across the terminals of any single cell; by some foreign substance or a piece of paste bridging over the space between a pair of plates; by the buckling of one or more plates till contact is formed between a grey and a brown; or by insufficient insulation of one or more cells, which would cause them to lose their charge when they were not supposed to be sending any current, and which would prevent them from receiving their legitimate strength of current when all the other cells in the circuit were being charged.

A short circuit can always be discovered by the cell thus affected showing no tendency to gas when all the others in the circuit are gassing, or by the hydrometer showing that the density of the acid in that cell is lower than that of the others at a time when they are all supposed to be charged.

When accumulators are not required for use for a considerable length of time, the precaution should always be taken of fully charging them before laying them aside. They should be all fully charged at least once every month while not in use, otherwise leakage and local action will be sufficient to discharge them partially, and sulphating will set in.

Sulphating usually shows itself in white spots on the brown plate; these quickly spread, covering the whole plate. Unless steps be taken to arrest the action, a white scaly substance is formed which chokes up the cell and ruins it.

There is only one cure for sulphating, and that cure is only effective when taken in time. It is continual charging with a moderate current till all trace of the white sulphate has disappeared from the brown plate. If the smallest trace of sulphate be allowed to remain, it will form a kind of nucleus from which sulphating will again assuredly spread. Sulphate on the brown plate reduces its effective surface, and therefore a proportionally small current must be used in charging, otherwise the cell will gas before it is charged and before the sulphate is reduced. This current may be gradually increased as the sulphate becomes reduced, when the normal charging current may be used. The cell must on no account be discharged till all the sulphate has been reduced, when the plate will recover its original brown colour, the sulphate having flaked off and fallen to the bottom of the cell.

BUCKLING.

After sulphating, buckling of the brown plates is the most usual cause of trouble in the management of accumulators. When the brown plate is being converted into peroxide of lead by the passage of a current it swells, gaining both in volume and weight. This phenomenon can be best observed where the brown plate consisted originally of common sheet lead. After being in use for some time, this sheet will have become considerably larger than it at first was, and if plenty of room is not allowed for this expansion the plate must of necessity begin to buckle; this buckling, once started, continues to increase at each fresh charging, till it finally short circuits the cell. The increase in the size of the plates is not so noticeable in the case of paste accumulators, for the reason that all the plates are fully formed before being fixed in their permanent positions, and also because but an extremely small portion of the grid is ever converted into peroxide of lead, the effective material consisting almost entirely of paste.

If two flat accumulator plates were fixed so as to be exactly parallel, and if their surfaces consisted of uniformly good conducting material, then if a current were sent from one plate to the other the current density would be evenly distributed over the surface of the two plates, and the same amount of peroxide would be formed at one point as at another. The brown plate would then expand uniformly, and, if sufficient room be allowed for this expansion, the plates would still remain parallel, though slightly closer to each other. If the plates had not been placed parallel in the first instance, or if they were not both quite flat, it is clear that the length of liquid separating them would not be the same at different points, and therefore the resistance would not be uniform between the different portions of the pair. Those portions of the brown plate which were nearest the grey would then receive a greater portion of the current than those which were more remote, and a correspondingly larger amount of peroxide of lead would be formed at those places. The expansion due to the formation of this peroxide would bring the already close portions still closer, and the density of the current passing at these points would be further augmented as the resistance decreased, while the more remote places would be robbed of their proper share of the current. Less peroxide would be formed at the distant portions of the plates than if the current density had been constant over the whole surface. Less expansion would go on at those places and, consequently, the strains being unevenly distributed over the plate, warping—or buckling, as it is usually termed—sets in. This buckling action increases at each fresh charging of the accumulators, and eventually ends in the plates touching and the accumulators becoming short circuited.

The second cause of buckling is of even more importance, since it is of more frequent occurrence. It is due to the fact that the brown plate does not present a uniformly good conducting surface to the passage of a current through it. If sulphating has taken place to any extent, that portion of its surface which has become coated with sulphate is comparatively inert. It offers a resistance far above that of the other portions of the plate, and consequently but a small proportion of the total current passes through it, while the healthy portions of the plate are obliged to carry currents far exceeding in strength any they would be called upon to carry in ordinary circumstances. Buckling of the brown plates is the necessary consequence. The formation of sulphate reduces the effective area of the brown plate in proportion to the amount of sulphate that has formed; in fact, the effective area of the plate is but little in excess of the area of healthy surface. It is for this reason that the charging current must be reduced when the plates have become partly sulphated, while it can be gradually increased to the original maximum as the sulphate becomes replaced by the healthy peroxide.

When but a small distance separates the plates—as was customary in the early forms of accumulators—any slight prominence on the surface of any plate considerably diminishes the resistance at that point, and allows an unfair amount of chemical action to take place there. When they are separated by a greater distance—as is now the case—the same prominence does not decrease the resistance in the same proportion, and the uniformity with which the current is distributed is less interfered with. Another point in favour of separating the plates is this: The grid is a better conductor than the paste pellets, and the current tends to flow through the good in preference to the bad conductor. If the plates are extremely close, the difference or resistance between the grid and the paste forms an appreciable part of the total resistance in circuit, and a greater current density passes across the liquid to the grid than passes to the pellet. The greater the distance that separates the plates, the greater is the resistance of the liquid, and, as the difference of resistance between the grid and pellet remains constant, it forms a less and less appreciable part of the total resistance in circuit as the plates are separated by increasing distances. More of the plate

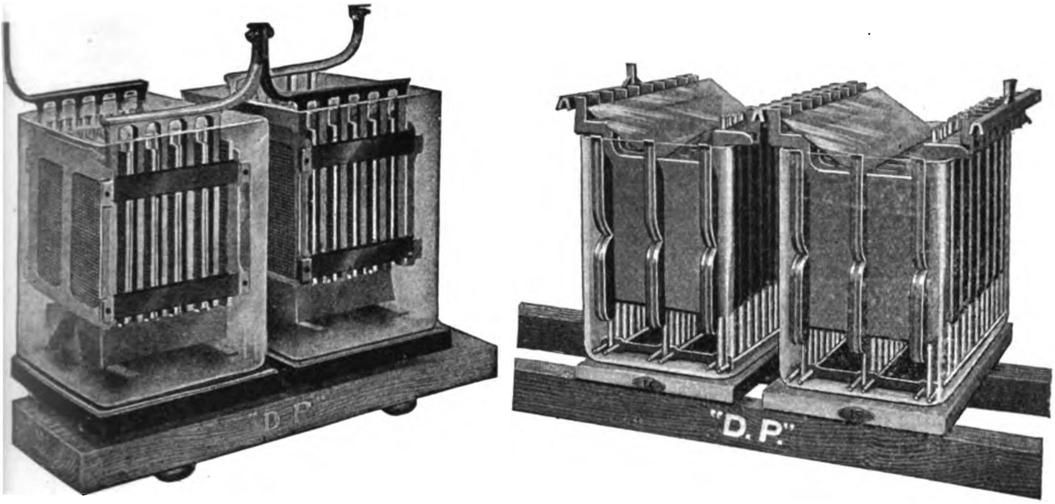


FIG. 43.—DETAILS OF CONNECTING AND ERECTING ACCUMULATORS: ON THE LEFT BOLTED CONNECTIONS, ON THE RIGHT "BURNT" CONNECTIONS; GLASS TUBES SEPARATING THE PLATES ARE SEEN ON THE RIGHT, ALSO GLASS SPRAY ARRESTERS.

is thus utilised as active material by the same amount of charging, and the life of the grid is prolonged by its being allowed to fulfil its proper function, which is that of a conducting reservoir for holding active material.

THE E.P.S. ACCUMULATOR.

One of the earliest accumulators to have any large practical application was that manufactured by the Electrical Power Storage Company, whose products have long been known as E.P.S. cells. The company commenced operations in 1882, working under the patents of Swan, Sellon and Volckmar, but its most successful work dates from its acquisition of the Faure patents for making pasted electrodes. This constituted what was almost a monopoly, since at that date Planté electrodes were not a commercial success. At the present day the E.P.S. accumulator is perhaps the only one in which both positive and negative electrodes are of the Faure, or pasted, type, the long experience of the company with this type of plate enabling them to make pasted electrodes for rapid discharges, while most other makers use formed positives. The largest cells have the electrodes supported upon glass slabs contained in lead-lined wooden boxes, a practice shared by other makers also. This construction is illustrated in Fig. 46. In some of their cells, however, the electrodes are still supported, directly or indirectly, upon the bottom of the box, and in this they also stand practically alone.

The "P" type contains electrodes about 14 inches square, may be discharged in one hour, and yields, at that rate, 50 ampere hours per positive plate. This rises to 105 at a seven-hour rate of discharge.

Various types are also made for special duties, notably that known as the Faure-King. This type of cell has much thicker plates than the ordinary E.P.S. type, and these are suitable for heavy currents. They discharge at about 10 amperes per brown plate.

They were introduced in 1896, and the large sizes give as much as 4·5 ampere hours per pound of complete cell. The capacity is from 30 to 40 ampere hours per positive plate at the five-hour rate of discharge.

GENERAL DETAILS.

There are various details connected with the erection and arrangement of a battery of accumulators which need consideration; the most important are enumerated below.

Stands.—The cells should be arranged on strong *wooden shelves* or racks, which should be protected with *shellac varnish* or other acid-proof paint. When more than one tier in height, a space of 30 inches should be allowed between the tiers.

Arrangement.—The batteries should only be arranged in double rows when they are accessible from each side. A space of an inch should be left between each cell, or half an inch between each tray.

Contacts.—The *contact surface* of the lead-connecting lugs must be scraped clean, the surfaces laid firmly together, and the *connecting bolts* firmly screwed up, after which the ends of the lugs above the bolt may be carefully soldered or burned together, so as to secure the metallic as well as mechanical junction.

The acid must not on any account be put in till the accumulator is ready for charging.

Poles.—The (+) positive pole (which pole of each section is always painted red) is to be connected to the (−) negative pole (which is always painted black) of the next cell through the battery. Thus there will be a disconnected positive terminal lug at one end and a disconnected negative terminal lug at the other end of the battery. These are the battery terminals which are to be connected with the dynamo circuit thus: the positive of battery to positive of dynamo, and negative to negative through a suitable switch.

Cells in Parallel.—Cells should never be connected in parallel, but whenever the capacity of a single cell is insufficient, separate batteries should be made up and connected in parallel by coupling these ends. Arrangements should be made so that the current in each battery circuit may be shown on ammeters.

Testing Dynamos for Polarity.—The dynamo before being connected should be tested for polarity, which may be done as follows. Place two clean strips of sheet lead in a stone jar filled with dilute acid; separate them a couple of inches by means of a block of wood, and connect one to a terminal of the dynamo, connect the other to one terminal of an incandescent lamp, and the other lamp terminal to the other terminal of the dynamo. After the dynamo has been running a few minutes, one of the lead strips will become brown, showing that the terminal connected with the strip is the positive (+). Specially prepared paper is also sold for this purpose, which, when moistened and brought into contact with the two wires from the dynamo turns a red colour at the point where the negative pole has touched the paper. Another method is to pass a current from the battery to the field magnet coils, maintaining the circuit for a few minutes—previously taking care to raise the brushes off the commutator—thus polarising the field magnets in the required direction.

Dynamo.—The dynamo used for charging should be shunt wound or separately excited, and the electromotive force should be specified in ordering the dynamo as at least 3·5 volts to 2·75 volts for each cell to be charged.

Filling Up.—When everything is ready for charging, and the dynamo has been tested for polarity, the acid solution is to be put into the cells to a height of not less than half an inch above the plates.

Mixing Acid.—If the solution be not purchased ready for use, "brimstone sulphuric" acid of 1·84 specific gravity must be slowly poured into the water in a separate and clean mixing vessel, well stirred and allowed to cool before the specific gravity is taken. The mixing requires to be done with great care, on account of the heat generated. If the water used is not soft and free from lime it should be previously boiled. The solution should stand for several hours after mixing, and should be occasionally stirred before it is put into the cells. The proportions by measure are about 21 parts of water to 4 parts of acid.

THE TUDOR ACCUMULATOR.

The brown plates, which are perhaps the most distinctive feature of these accumulators, are lead plates of large surface, and are formed on the Planté method. The large surface is due to the peculiar form in which they are cast. The plates are formed by a process very similar to the one originally designed by M. Gaston Planté, modified only so far as to ensure greater adherence and homogeneity, and to obtain greater rapidity in formation without the use of corrosive acids.

In the casting shop are two large melting pots, each capable of holding about two tons of lead. The one pot contains pure lead, from which the brown and most of the grey plates are made. The second pot contains an alloy of lead with a small quantity of antimony, which is used for certain small accessories and for the large type of grey plates. The manufacturers attach considerable importance to the purity of the lead used in the plates, and much of the success achieved by this accumulator is possibly due to this fact. However that may be, they certainly insist upon obtaining the best brands, which can be guaranteed to contain less than 0·1 per cent. of impurities. Also, all water used both in the construction and formation of the plates is distilled.

The moulds in which the plates are cast are in halves, each corresponding to one side of the plate, and consisting of a rectangular cast-iron frame, in which are held a number of gun-metal racks, 15 mm. wide, cut with very fine teeth. A very slight space is left between each rack, corresponding to a horizontal rib on the plate; at intervals of about 120 mm., a tooth is cut away on each rack, so as to give an extra strong vertical rib at those points. These vertical and horizontal ribs and the strengthened edges, while giving greater rigidity to the plates, provide paths for the current, of which they thoroughly ensure the even distribution. Slots are cut in the cast-iron frame, so that the lugs and strengthened edges are cast in one piece with the rest of the plate.

The two portions of the mould are mounted in a vice, one side of which is fixed, the other being movable, first for an inch, parallel to itself, and then about an axis, so as to open the mould entirely for the removal of the plate.

In the brown plate, when the mould is closed, the apices of the teeth do not touch, and a thin backing is formed, the pitch of the teeth being about 2½ mm., and their depth 6 mm. In the moulds for the grey plates, which consist of an open grid, the teeth on either side touch when the mould is closed, and the thickness of the teeth on the rack is much greater.

It is, of course, of the utmost importance that the teeth should be cut with great accuracy, and they are made as rectangular as possible, avoiding all sharp edges on the surface of the plate, which would rapidly become worn out. For the purpose of forming, the brown plates are then brought into the formation rooms, where they are mounted in lead-lined wooden boxes. The plates are hung from glass sheets, and are burnt to temporary lead-connecting bars, in much the same way as they are usually mounted in the cells. The plates, both brown and grey, are of the brown, large-surface type, the cells being filled with dilute sulphuric acid only. The peroxide of lead on the surface of the plates is produced first by alternately charging the cells and leaving them on open circuit, and afterwards by alternately charging and discharging them at frequent intervals throughout the day, the discharge becoming heavier as the formation advances. Finally the cells are charged and discharged under the ordinary conditions until they attain very nearly the normal capacity, when the plates that have been used as brown in the formation are removed and dried.

The process lasts about six weeks, and is carried out as continuously as possible, day and night.

To prepare the grey plates, the grids are first "pickled" by charging them brown with a heavy current for a few seconds. They are then filled in the ordinary way with litharge, formed into a paste with sulphuric acid. After being dried, the majority of grey plates are sent out without further preparation. It has been found that the active material of the grey plates, which is lead in an extremely fine and divided state, oxidises and sulphates so readily that the time required for reducing them after erection is scarcely lessened by a previous reduction of the litharge at the works. On the other hand, grey plates previously reduced have always a tendency to scale and blister during the first charge, owing to the hard coating of sulphate of lead on their surface.

The cells are made in various sizes in order to provide convenience of handling under various conditions. For example, where there is ample floor space, the plates are approximately square, and two sizes of square plates are made, to give different capacities without running to too high a number of plates in one cell. Where floor space is valuable, a plate that is deep from top to bottom is used.

Of these cells two full working drawings are shown in Figs. 44 and 45, as well as the general arrangement of setting up and connecting.

Fig. 44 shows the glass-cell type as mounted for stationary work. It will be seen that each plate has its lugs bent over the side of the glass vessel, and that the plate is suspended in the cell by these lugs resting on the edges of the glass. A clear space of some four inches is thus left underneath the plates, and very little risk is thereby incurred of short circuiting the cell by the mud which always accumulates at the bottom.

The glass separators are half an inch in diameter and run right to the bottom of the cell. At the top they used to pass between the lugs and small projections on the top of the plates, and were separated from both by two glass strips running along the tops of the plates. This device not only kept the separators in position, but also acted as a support for the ends of the plates which are remote from the lugs. The method of supporting the cells on insulators, of connecting the cells together, of taking the connections from them, and other details are clearly shown in the drawings.

The Type B is shown in Fig. 45, where the general arrangement is similar to Type A, with the obvious difference that the lugs of the plates cannot now rest on the sides of the containing vessels, which consist of lead-lined wooden boxes. They rest instead on the edges of two glass plates which are placed on end, the lower edges of which rest on the floors of the cells. This arrangement is evidently not so rigid as the other, but it is made more stable by using three glass separators instead of two, the central one of which is maintained in position by two small projections on the plates. All other details are shown in the drawings.

For the largest type of plate, known by the makers as the Type C, the lugs are removed from two brown Type B plates, which are solidly burnt to two hard lead strips. These side strips are cast in one piece with the connecting and suspending lugs. A space of about half an inch is left

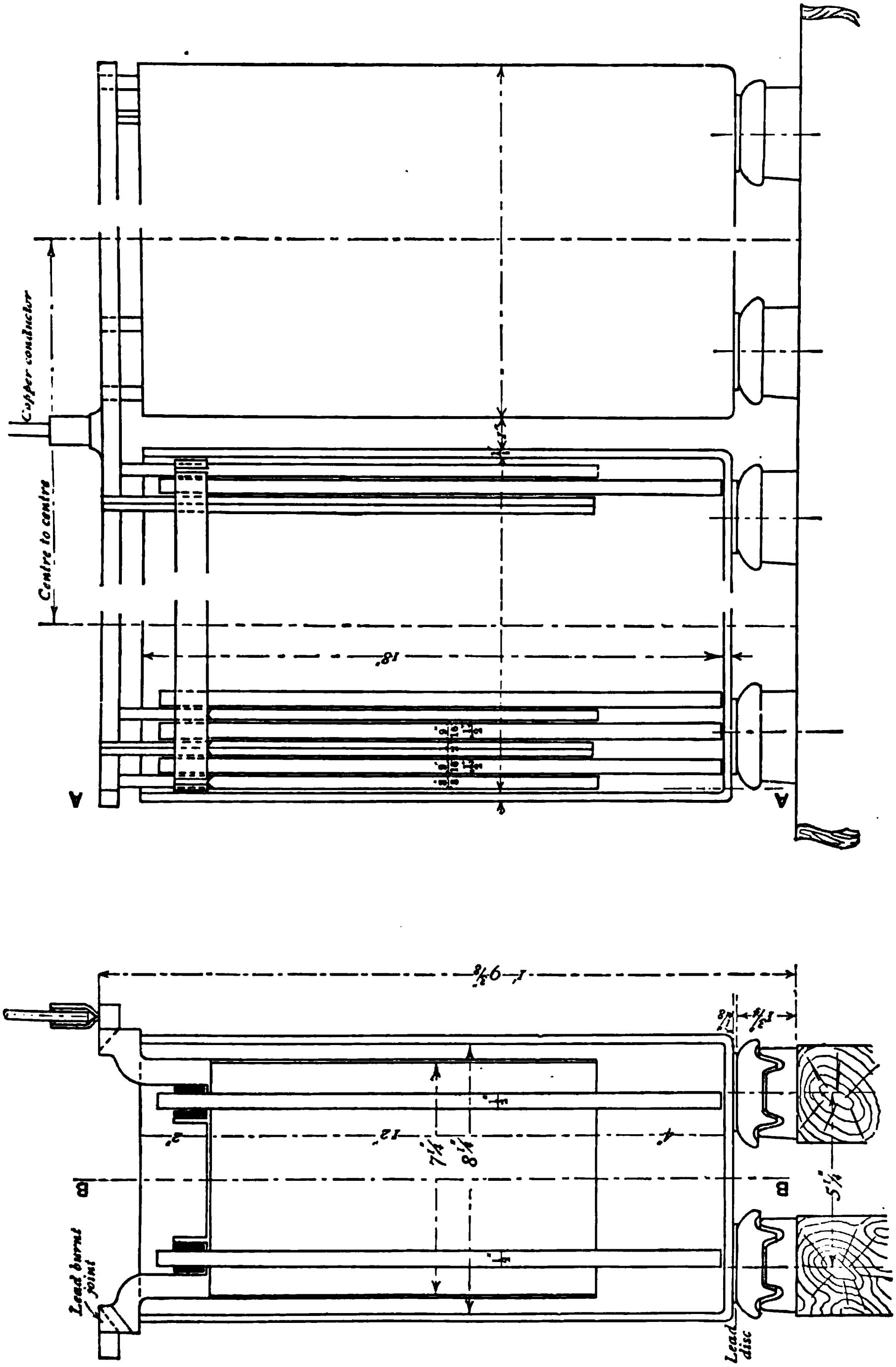


FIG. 44.—TUDOR ACCUMULATOR (TYPE A) IN GLASS BOXES.

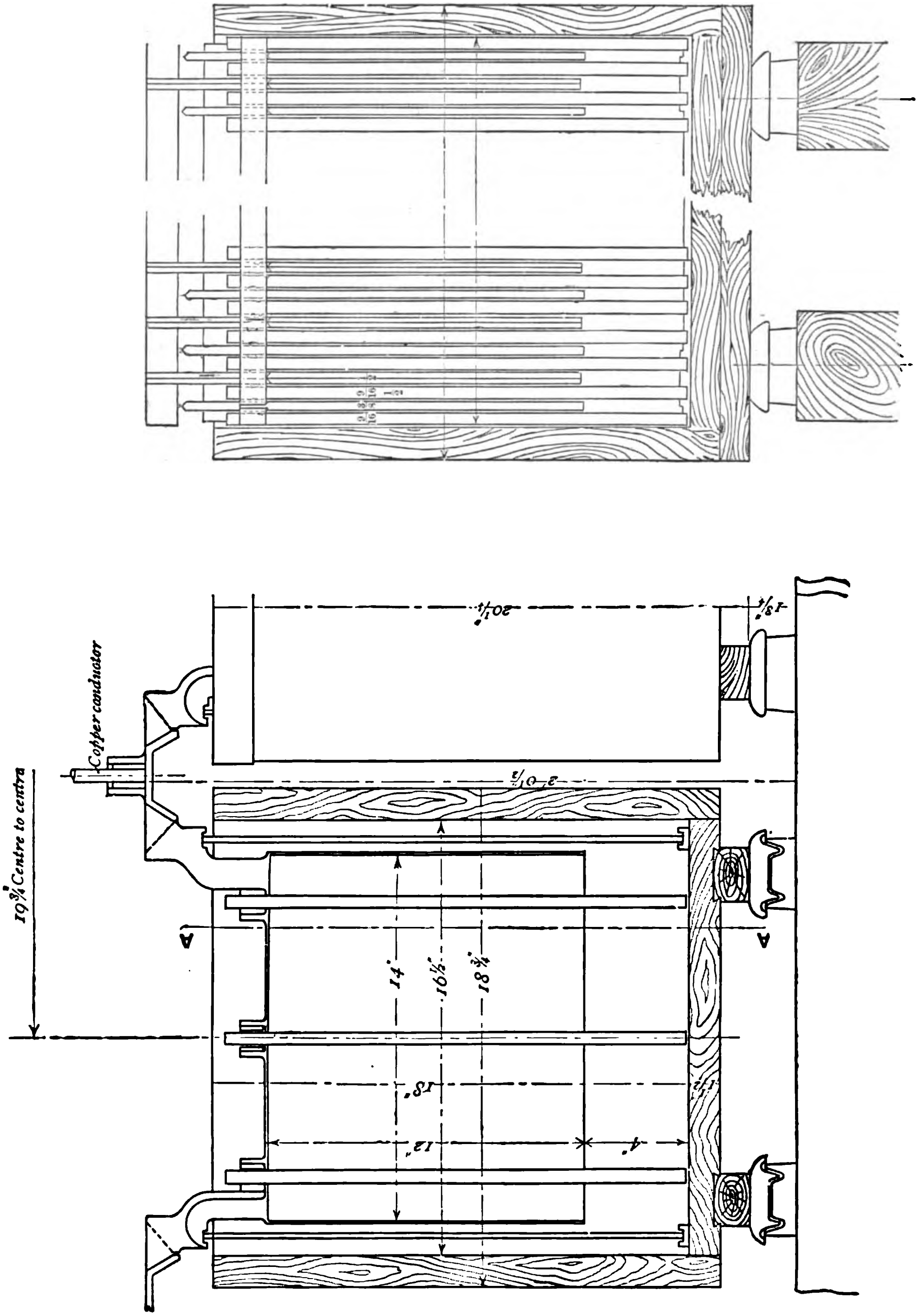


FIG. 45.—TUDOR ACCUMULATOR (TYPE B) IN LEAD-LINED WOOD BOXES.

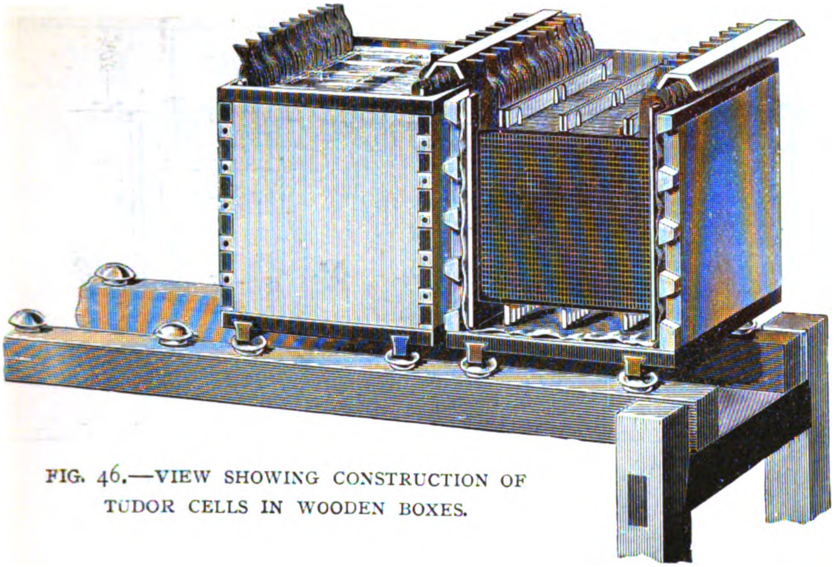


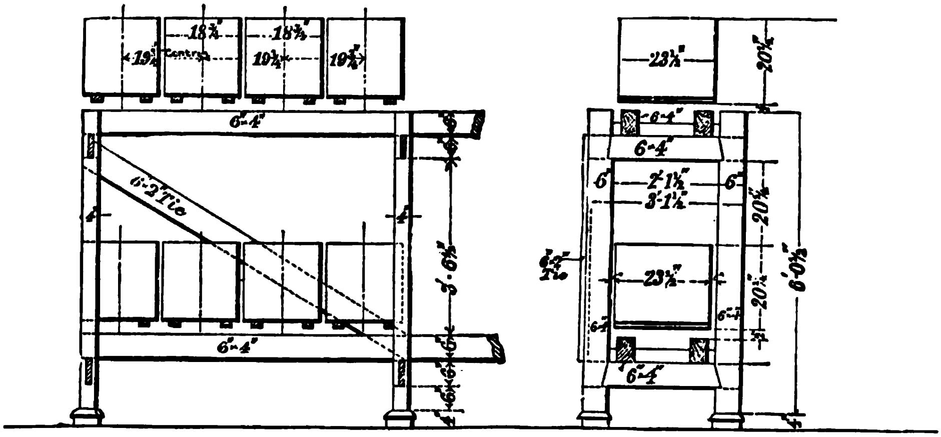
FIG. 46.—VIEW SHOWING CONSTRUCTION OF TUDOR CELLS IN WOODEN BOXES.

between the two plates so as to allow for their expansion in ordinary working. The size of the finished plate is about 16 in. wide × 25 in. high. The grey C plates are made of two grey B plates, the lower edge of one being solidly burnt to the upper edge of the other. To give greater rigidity to grey plates of this size, they are made of antimony lead alloy.

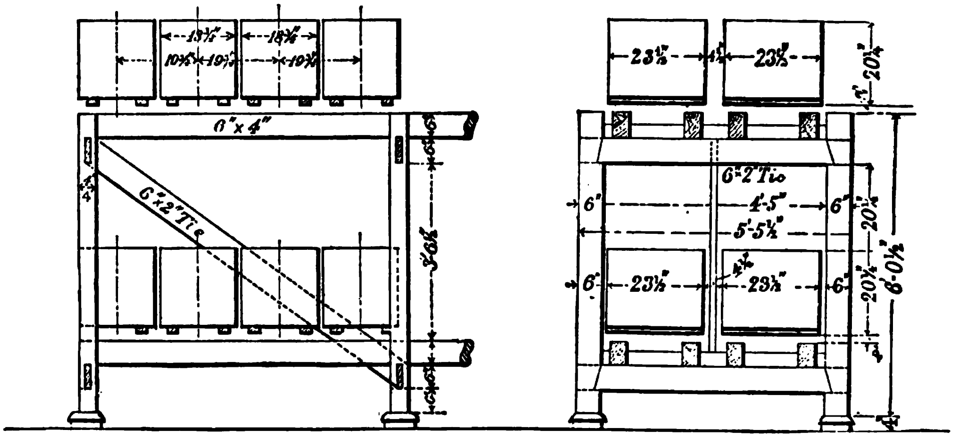
One of these batteries is in use at Tontine Lane, Glasgow. This battery is composed of 134 cells, Type H.C. 27, each containing 27 plates of the C type. The output is 2,080 ampere hours, or 1,040 amperes for two hours, with a minimum voltage of 240 volts. The cells are capable of giving a current of 780 amperes for three hours. The size of each box is 2 ft. 9 in. × 1 ft. 11 in. × 3 ft. high, and the weight of each cell when filled with acid is 18 cwt., making a total weight of 120 tons for the whole battery. The general appearance of the cells as joined up is shown in Fig. 46. The dimensions for a stand and battery of B type cells with 21 plates are given in Fig. 47, arrangements being shown for both a single and double row. Frequently too little attention is paid to fixing the cells in position; where possible, access to the cells should be provided on both sides. The room must be well ventilated to allow escape of the gas and acid spray given off during charging.

USE OF ACCUMULATORS.

The use to which accumulators are put varies somewhat with the character of the installation using them. For the isolated house plant, they have for many years held a well-deserved position of confidence, while until recently the large central station may be said to have regarded its accumulator as a necessary but almost unmitigated evil. The main difference lies in the fact that the treatment meted out to the accumulator in the private house plant can be of a regular and unvarying kind. The engine, whether steam, gas, or oil, is usually put to work during the hours of daylight to charge the battery, which is generally so proportioned to the load as to need at most some seven hours' charge at normal current in winter. Discharge follows during the evening and following early morning, only to be



ELEVATION. END VIEW.



ELEVATION. END VIEW.

FIG. 47.—DIMENSIONS FOR STAND AND BATTERY OF B TYPE TUDOR CELLS IN SINGLE AND DOUBLE ROW.

followed in turn by the requisite charging. Such regular treatment is the essence of good health for an accumulator, and is just that which the uncertainties of Central Station working forbid. Moreover while the variation of voltage was regulated by cutting one or two cells at one end of the battery in or out as the case required, these end cells of a central-station battery had a very short life, and were expensive to renew. The advent of the reversible booster has at once eliminated the end regulating cells and improved the life of the whole battery.

ACCUMULATORS AS RESERVOIRS.

An isolated installation of electric light where accumulators are not used can never be thoroughly depended upon, while, when used, they have the additional advantage that the machinery need only be run during the day, or in the ordinary working hours, or at any odd time when it may be found convenient to run it. Again, when but a few lights are required it would be absurd to be obliged to run an engine and dynamo for supplying as much light as could be got from half a dozen gas-burners, yet if accumulators are not used it would be necessary to do so. The same amount of light could be got from accumulators at any time, day or night, without seriously affecting the total charge stored up in them. They can be discharged at any rate, from 1 ampere up to the maximum discharging current, and they are thus in a position to meet any demand, however great—within these limits—that can be made upon them. Their efficiency is not the same for all rates of discharge, though it does not greatly alter, owing to the fact that the internal resistance decreases with the amount of current passing. It is, however, found that for stationary installation work the most economical rate of discharge is that which will completely discharge them in about ten hours; while for other kinds of work—such as tramcars, electric launches, etc.—a higher rate, which will discharge them in about six hours, is advisable. In small installation work, however, the question of efficiency is one of but minor importance as compared with that of absolute trustworthiness and convenience. For central-station work efficiency is a necessity, but for small installation work it dwindles into comparative insignificance when the other items of expenditure are taken into account. Where water power can be procured free of cost the question of efficiency vanishes, excepting in the part which it plays in depreciation of stock. From the makers' lists the type and number of accumulators necessary for any installation can at once be selected. The E.M.F. is the same for any type, but the number of amperes that each can supply depends upon the area of the plates. The type depends entirely upon the maximum current required, and can therefore be selected at once, while the number depends upon the voltage of lamps used. A practical rule for the number of accumulators required for any installation is this: Divide the voltage of the circuit by 1·8, allowing about 2 per cent. extra for drop in cables. The cells, when nearly discharged, will keep up the voltage, and when fully charged, must have end cells cut out or a back E.M.F. interposed. Thus 57 cells are ample for a 100-volt circuit.

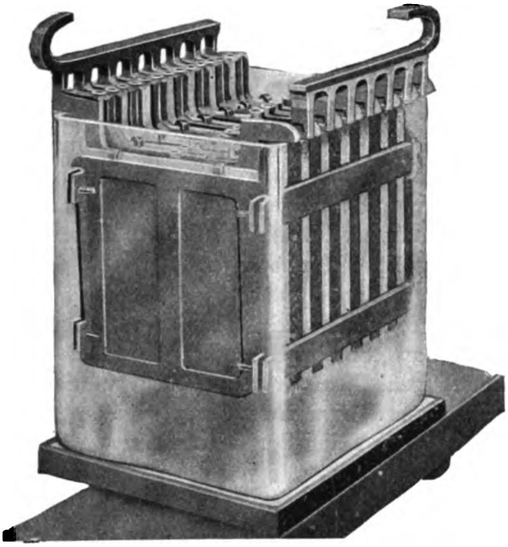


FIG. 48.—"D.P." ACCUMULATOR SHOWING MODERN PRACTICE OF SUSPENDING PLATES AND GIVING CLEARANCE BELOW THEM.

ACCUMULATORS AS REGULATORS.

Accumulators were for many years used in central stations in order to improve the efficiency of the station as a whole. This efficiency may be seriously impaired if the station plant has to be kept continuously running during hours of light load. The inefficiency under such conditions arises not only from the fact that men must be in attendance on the boilers, engines, and switchboard to earn a very small revenue for the undertaking, but also from the fact that the load is so small in proportion to the size of generating unit employed, that the engine and dynamo are working very inefficiently. Thus both the labour charges and the coal charges are heavy in proportion to the units sold. The addition of an accumulator may improve matters in either or both of these respects, for it may enable the hours of labour to be reduced by taking the whole of the light load from, say, 10 p.m. to 6 a.m., and may enable the engineer in charge so to arrange the running of his machinery that when the ordinary load would result in inefficient working, he can choose that period for charging his accumulator. A further advantage to be derived is that the accumulator may sometimes suffice to meet a sudden peak load or a temporary emergency caused by a breakdown, while spare machinery is being got into motion.

SPECIAL ACCUMULATORS.

Certain interesting methods of constructing accumulators will now be described, the first two being of merely historic interest.

The latest improvement in the Chloride cell is the use of sheet wood separators, of the same size as the electrodes. The negatives are made like envelopes of perforated sheet lead containing litharge.

THE CROMPTON-HOWELL ACCUMULATOR.

Mr. Howell invented a process of producing lead plates for storage batteries by the use of porous lead made by maintaining melted lead almost at the point of crystallisation, and then casting from the semi-crystalline mass blocks of what may be called lead sponge—that is to say, blocks which consist of a number of lead crystals, all held firmly together at their points of contact. Such lead sponge, when sawn into plates of suitable size, gives results which show it to be the most reliable material that has yet been used in the manufacture of accumulator plates.

By an adaptation of the very simple process of formation invented by Gaston Planté, it is possible to form the enormously extended surface of this lead sponge into lead peroxide or finely divided chemically active lead, in the one case forming the brown plates of the batteries, and in the latter case the grey plates.

The whole structure of the plates is entirely crystalline, yet so very porous that almost every individual crystal is freely bathed by the electrolyte, thus presenting a very large surface material. The active material, in being deposited electrically, forms a coating firmly adherent to the lead crystals; and as this electro deposit is formed right through the plate, it does not readily fall away, and the intimate connection between the fine crystalline labyrinth at back and the coating of active material reduces the resistance to a minimum. Plates thus made and prepared are free from most of the defects which are inherent in pasted plates. The lead salts which form the active material, instead of being artificially made and mechanically placed in position in the form of paste, are by this method electrically and chemically formed as a firmly adherent deposit on the greatly extended surface of the crystals themselves, and are therefore dispersed right through the spongy material. Thus it is impossible for the active material to become detached or fall off to any serious degree, as it extends so thoroughly into the very substance of the plate itself that it is completely interlocked with it, and cannot escape or be removed without practically grinding the plate to powder.

THE EPSTEIN ACCUMULATOR.

This accumulator consists of lead plates about half an inch thick, and in order to increase its area a number of horizontal grooves are cut along its sides.

The effective area of the plates is by this means more than doubled without unduly weakening them. During formation the saw-cuts in the brown plates become partly filled with peroxide, so that they lose the sharp edges and become gradually rounded off.

The method of shortening the process of manufacture is a kind of pickling which results in the exposure of a large amount of plate to the action of the acid.

The plates are placed in a 1 per cent. solution of nitric acid, and the whole boiled for a couple of hours. At the end of that time the plates will have turned a dull greyish colour. During the boiling the acid attacks the lead and thoroughly honeycombs it to a considerable depth beneath the exposed surface. The interstices thus formed are filled with lead salts, which are insoluble in dilute sulphuric acid, but which are readily reduced by the gases evolved when the acid is decomposed by the passage of a current. The plates are now ready to be "formed," which operation is only a question of hours, and which involves no reversal of the current.

THE CHLORIDE ACCUMULATOR.

The construction of the grey plate is begun with the manufacture of the paste, and here litharge forms the basis. This substance is sprinkled into large vessels containing acetic acid, and the mixture maintained in a violent state of agitation, with the result that the whole is converted into acetate of lead, which is run into cisterns and allowed to settle. It is now treated with hydrochloric acid, and finally forced through a filter press by means of a steam pump. The hydrochloric acid unites with the lead in the acetate of lead and is retained in the filter, whilst the acetic is run off into tanks and can be used over again. The chloride of lead which remains behind in the filter in the form of a white paste is next carried into drying ovens, where it remains for some eighteen hours till all moisture is driven off and it resembles a mass of chalk, which is stored in bins.

MAKING THE PASTILLES.

From the bins the lead chloride is taken and mixed with finely divided metallic zinc, the whole being next placed in large melting pots and subjected to intense heat till it runs into the fluid state.

This chloride is next ladled out with plumbago crucibles and cast into pastilles in an iron mould. These pastilles are hexagonal in shape, and have two small holes passing through them.

The small pastilles are conveyed by the thousand on enamelled steel trays to the plate framers, where they are first placed by boys in the plate moulds—cast-iron plates recessed to the pattern of the plate eventually to be cast, and bristling over with tiny pegs, the two holes in each pastille mentioned before coinciding with two of the pegs in the mould. By this means the pastilles are arranged regularly in the mould, and also prevented from altering their position when the lead which forms the frame is forced around them. This is an interesting process, and if not carefully carried out might be dangerous. For the mould having been closed by hydraulic pressure, the nozzle of the lead chamber in the lead-casting machine is drawn into the mouth of the mould by a screw. Compressed air is then turned upon the chambers in a large lead pot, and with a rush the lead is forced through the nozzle into the mould, and completely fills all the interstices, making a complete frame round the pastilles. Each lead pan is fitted with four presses round it, which form part of the machine, and the compressed air is delivered into the lead chambers at 150 lb. to the square inch by special machinery. To prevent accidents, the various parts of the machine are so interlocked as to make it impossible to apply the pneumatic pressure to the lead chambers until the press has been completely closed. The machine is also constructed with shields jutting from it, behind which one takes refuge as the lead is forced in, in case anything should go wrong.

The plates, which have now been formed, and which consist of rectangles of lead thickly studded with hexagons of chloride of lead, are trimmed by a circular saw so as to make the edges perfectly smooth and regular. In the reducing sheds the plates are put into reducing tanks sandwiched up with zinc plates and submerged in liquid chloride of zinc. No sooner is the plate put into the chloride of zinc bath than all the chlorine immediately separates from the chloride of lead and unites with the zinc, forming chloride of zinc, leaving the lead "spongy." Next, the plates are put in continuously running water tanks, where they are washed with pure water for about a couple of days, after which they are transferred to a forming bath. Here they are coupled up with permanent brown plates in a weak solution of sulphuric acid, and a heavy current is passed through them. Hydrogen is violently evolved and combines with the last trace of chlorine that may have remained after the reducing process. The pastilles have now been converted into chemically pure lead. These plates are the grey plates, and they are now ready for casting up and sending out, to be dealt with along with the brown ones in the formation of an accumulator.

I will now proceed briefly to sketch the formation of the brown plates. The brown plate starts in a fashion directly opposite to that of the grey plate. To commence making it, you start with absolutely pure lead tape, which is wound by miles on drums. This tape is then passed through specially designed gimpers, which gimp the strips and cut them up into definite lengths. Of course, they can be so adjusted to cut to any length as may be required.

When the lead is gimped, it is taken by boys and wound on a specially designed winder, which curls up each length of tape into a circular pastille, and it is then seen that the effect of the gimping has been to expose a far greater surface than would have been the case had the tape been left perfectly plain. These circular pastilles are next taken to the fillers. They put them into plates of antimonical lead, pierced with small circular holes, which taper each way and which almost touch one another, and into each circular hole a pastille is forced. After filling, these are put into a powerful hydraulic press, under a pressure of 75 tons. The grids into which the pastilles are inserted are made in moulds, and the lead is forced into them in exactly the same way as the frame was formed, under pneumatic pressure round the pastilles with chloride of lead, in the grey plates. When the round lead pastilles have been inserted in the brown plates, they are taken off to the forming department, a large room resembling that in which the grey plates are kept in their respective baths. In the forming cells brown and grey plates are alternated just as they will be in the finished battery, the bath being fitted with permanent grey plates. Here they are kept three or four days, with a current passing through them all the time, when, ultimately, the pastilles become covered with a thin crystalline coating of peroxide of lead. The plates are then placed in running water and washed, and then cast into sections for sending out.

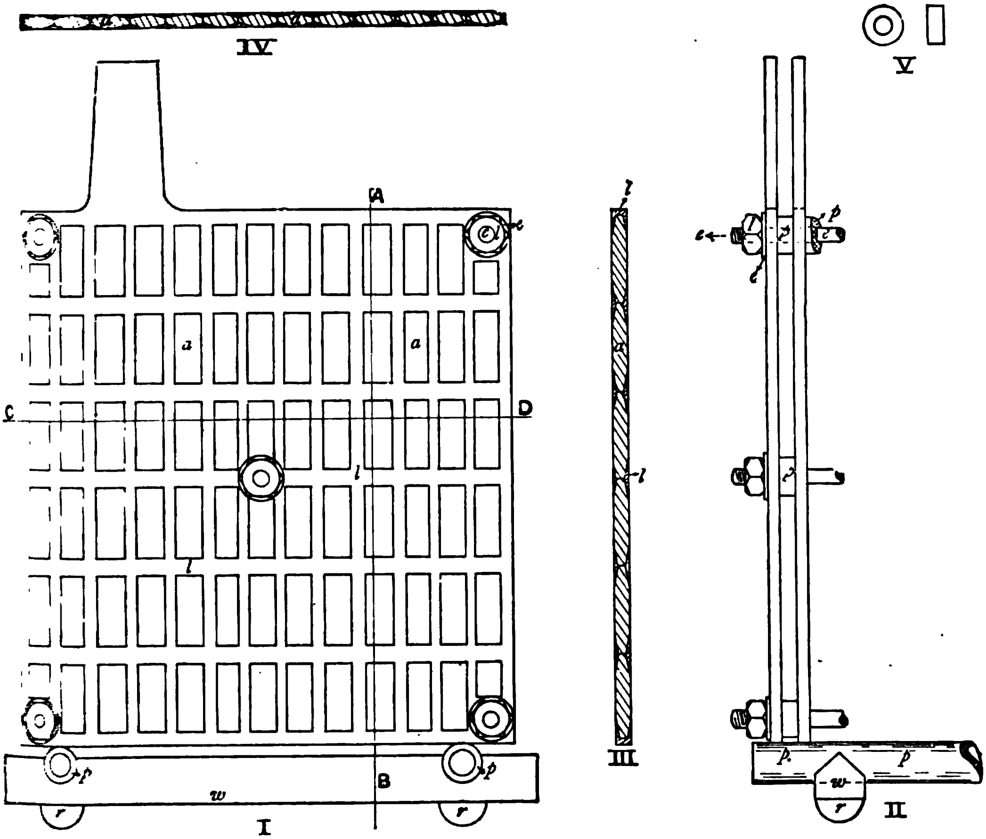


FIG. 49.—PLATES OF LITHANODE ACCUMULATOR

THE LITHANODE ACCUMULATOR.

This cell was originally made under the patents of Mr. Desmond Fitzgerald, but those of Mr. J. T. Niblett are now possessed by the same company. The following brief description of the construction of the cell is taken from Mr. Niblett :—

Lithanode is not compressed peroxide of lead, as is sometimes supposed; for, however strongly this lead peroxide may be compressed, the resulting mass will disintegrate when immersed in a liquid electrolyte. It is produced from litharge made into a pasty mass with a solution of sulphate of ammonia, which causes the material to "set," so that it will no longer disintegrate when placed in a fluid. The forming according to the original idea was performed in a bath of sulphate of magnesia. In ordinary practice the elements are made up of a number of small slabs of lithanode, whose outer edges are V-shaped. These slabs or pellets are arranged in a casting mould of any suitable dimensions, and are placed at such a distance apart and from the edges of the casting frame as to allow of sufficient space for the requisite quantity to run in and impart adequate mechanical strength to the completed element. After the pellets have been arranged in this manner, an alloy of lead and anti-

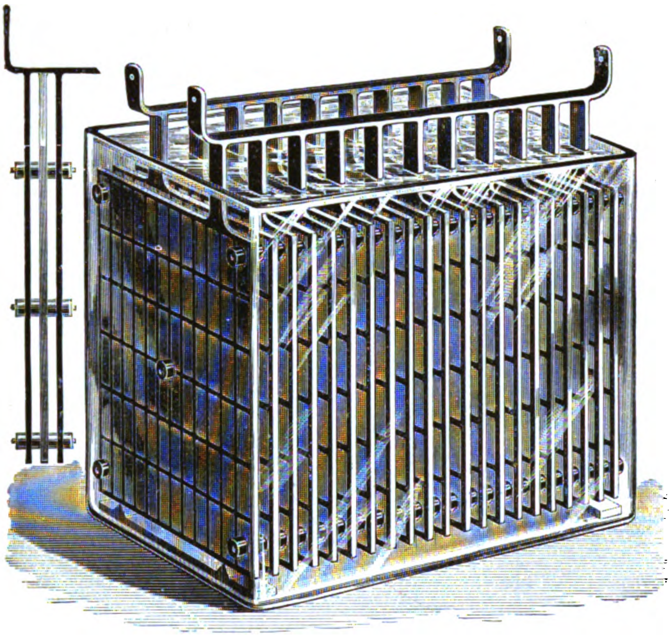


FIG. 50.—LITHANODE ACCUMULATOR CELL.

mony is run into the interstices, and thus a complete plate is formed. The scale drawings of such a plate are shown in Fig. 49, as well as the full details for setting up and separating the plates. Fig. 50 shows the finished accumulator.

Before being cast up the brown pellets are converted into peroxide of lead in the forming bath ; those for the grey plates are simply dried and cast up direct, the lithanode in the latter case being reduced to a condition of spongy lead by the ordinary electrolytic method.

When lightness is a desideratum, as in the case of traction cells, the pellets in the brown plates are made larger. while the grey plates are constructed of lead gauze, having its outer edge strengthened by a rim of lead. The gauze is filled in with the prepared litharge, which entangles itself in the thin lead wire and thus produces a plate of great lightness, and one little liable to fall to pieces.

Lithanode may be obtained in varying degrees of porosity. For high discharges it is made of a highly porous nature, the porosity being produced by incorporating crystals of some salt which is practically inert, and which is dissolved out during the forming operation.

The discharge obtainable from one of these batteries varies between very wide limits, and is regulated by the character of the lithanode, whether made hard, medium, or soft. The ordinary working rate of discharge is $\frac{1}{14}$ of an ampere per square inch of lithanode plate, but owing to recent improvements very much higher rates can be obtained. The electrical capacity of lithanode when discharged at the above rate is almost exactly one ampere-hour per ounce, so that with an element weighing 1 lb. a current capacity of 16 ampere-hours is obtained. In practice, however, this high capacity is never reached.

SECTION III.

ELECTRO-DEPOSITION OF METALS.

CHAPTER I.—INTRODUCTORY.

UNDER this heading it is proposed to give workshop methods for depositing the practical metals of commerce, which include gold, silver, copper, brass, iron, nickel, and zinc.

Electro-deposition is divided into two distinct parts, viz. electroplating and electrotyping. The first consists of coating any metal with another, or similar, metal which is intended to adhere inseparably to the first ; the second comprises all the cases in which the deposited metal is separated from its basis, which may or may not be metal. An electrotype thus forms in itself a separate object, whereas electroplating only decorates or protects a metal basis. The word electroplating is generally used to mean plating with silver, electroplating by any other metal is usually designated by the metal deposited, thus—brassing, nickeling, steel-facing, etc. ; although, of course, both processes are plating and coating electrically a metal basis.

Electrotyping can be also divided into two parts :—

1. That comprising the reproduction of works of art, or of objects which serve a decorative as well as a useful purpose; and which necessitates the deposited metal being sufficiently thick to be itself the substantial portion of the finished work.

2. Electrotyping for printing purposes (which may or may not comprise in itself the printing plate, the reproduction of wood blocks, etc.) consists of a film of copper backed with type metal and a wooden block, speed and cheapness necessitating this mode of reproduction. For the reproductions of high-class plates, such as those used for printing bank notes and good photo reproductions, etc., the electrotype is carried to a sufficient thickness (depending on the area of the plate) to be complete in itself.

It is in the moulding for these two classes of electrotyping that the chief difference between them lies.

A printing surface is usually flat, in extremely low relief, and in a hard material, such as wood, metal, etc., whereas in art reproductions the base is usually wax or clay, and may be in high relief, undercut, or in the round.

Electroplating is treated in these pages as follows :—

1. The formula and preparation of the solutions for depositing copper, silver, brass, zinc, nickel, iron, gold.

2. The preparation of the auxiliary dips, acids, etc., for the proper plating of various bases with the above metals.

3. A description of tanks, vessels, etc., for containing the above, and the requisite fittings for the vats, including resistances and measuring instruments.

4. The preparation of work and routine to be followed in the passage of various metals to the above baths and management whilst immersed.

5. The finishing of plated work, which includes polishing, colouring, oxidising, lacquering, etc.

6. The general arrangement of a plating

shop, its dynamo, polishing spindles, scratch brush spindles, steam arrangements, pumps, etc.

7. Explanation of the fundamental laws, chemical and electrical, governing the deposition of the metals, with tables of the elements, equivalents, synonyms, weights, measures, etc.

Electrotyping comprises :—

1. The copper solution : its management and possibilities.

2. Moulding processes. These may be subdivided under four headings, of which detailed descriptions are given :—

(*a*) Preparation of the surfaces of various materials from which a mould may be taken.

(*b*) The preparation and uses of various moulding materials, such as plaster-of-paris, gelatine, gutta-percha, wax, etc.

(*c*) The moulding of low relief, undercut and high relief, and work in the round.

(*d*) Moulding of printing surfaces with the press, etc.

CHAPTER II.—ELECTROPLATING.

PREPARATION OF BATHS—PREPARATION OF SILVER-PLATING SOLUTION—BRIGHT SILVER SOLUTION—BRASSING SOLUTIONS—COPPER SOLUTIONS—NICKEL SOLUTION—GILDING SOLUTIONS—AUXILIARY SOLUTIONS—STRIPPING AND STRIPPING SOLUTIONS—NICKEL STRIPPING SOLUTION—STRIPPING GOLD FROM GILDED WORK—CONTAINING TANKS, VATS, ETC.—APPARATUS FOR PREPARING SURFACES TO BE PLATED.

PREPARATION OF THE BATHS.

IN the following pages the weights will be given in grammes and ounces, the precious metals in troy weight, and the salts and base metals in avoirdupois; the fluids in litres and the English fluid ounces, pints, gallons, etc. (Fluids are measured by volume, not by weight.) In making up stock solutions such as cyanide, carbonate of potash, etc., it is always well to make them up to some uniform strength, so that at any time there may be no doubt as to the amount of salt a solution contains. Thus, a 25 per cent. solution of cyanide means that every fluid ounce contains ¼ oz. of cyanide salt.

To make up solutions of a definite percentage, say a pint of 25 per cent. carbonate of potash, dissolve by heat 5 oz. of the potash salt in 10 oz. of water, and when dissolved, add water to make up a pint.

Precipitations should never be made in concentrated solutions. A good degree of dilution of the precipitates and of the solutions from which the salt is to be precipitated is that given above—25 per cent.

Small bulks of these solutions are made in boiling flasks, and their precipitates collected on filter papers; large bulks in large glass bottles, and their precipitates allowed to subside sufficiently to decant off the wash waters, etc.

For dissolving large bulks of salts, etc., boiling water can be put into earthenware pans, and the salt to be dissolved tied up in a paperhanger's canvas bag and (Fig. 51) suspended from a rod so as to be just immersed in the water. By this means the water that is charged with the dissolved salts, becoming heavier than the rest, sinks to the bottom, and fresh, uncharged water takes its place. This circulation continues until either all the salt has been dissolved or the water is unable to dissolve any more. On this account the bag should be only just immersed. If this method is not employed, and the salt is put loose into the pan, frequent stirring will be needed to obtain a complete solution.

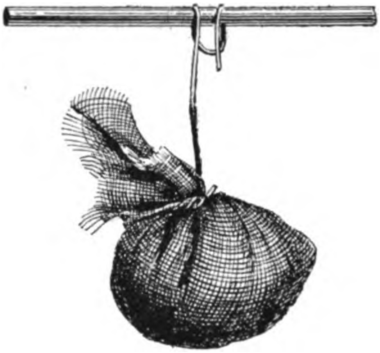


FIG. 51.—METHOD OF DISSOLVING SALTS.

In the following solutions the salts are prepared at home instead of being purchased from a shop, for the reason that only freshly prepared salts should be employed. All precipitates should be redissolved at latest the same day as prepared, and left as little exposed to the air as possible. This avoids the formation of basic salts, which require a greater proportion of the solvent, thus upsetting the equilibrium of the solutions, especially in the case of the carbonates.

In the following pages only one formula is given for the preparation of each bath, and that is the one most generally used in practice, having been found to give the best results with the least amount of trouble.

An enumeration of the countless solutions which *will* give a deposit of the desired metal is only useful in an experimental laboratory.

THE PREPARATION OF THE SILVER-PLATING SOLUTION.

There is only one silver-plating solution that the practical electroplater need take into consideration, and that is the double cyanide of silver and potassium. Three modifications of this solution are all that any plating shop requires. They are :—

(*a*) Double cyanide of silver solution, containing 2 to 4 oz. of metal per gallon for heavy plating.

(*b*) A solution same as above, but treated with bisulphide of carbon, to obtain a brighter deposit than that obtained naturally from the ordinary solution.

(*c*) The striking solution, containing a small amount of silver with a large excess of cyanide, *and used hot.*

The principal working solution of silver should not contain less than two ounces of silver per gallon. A good deposit can be obtained with as little as one ounce of metal, but for quick and heavy plating one with four ounces per gallon is preferable.

The method of preparation given below starts from the metal, and is somewhat cheaper per ounce of metal than purchasing the silver nitrate ; it has the further advantage of giving definitely the metal content of the solution. Recrystallised silver nitrate should contain 63·5 per cent. of metal.

The formula for 1 gallon of silver solution is as follows :—

Silver (granulated), 2 oz. = 62·207 grammes.

Nitric acid (1.420 sp. g.), 2 oz. = 56·792 cubic centimetres.

Potassium cyanide (98 per cent.), 4 oz. = 113·39 grammes.

Water, 1 gal. = 4·542 litres.

Or if made from the salt :—

Silver nitrate (63·5 per cent.), 3¼ oz. = 92·9 grammes.

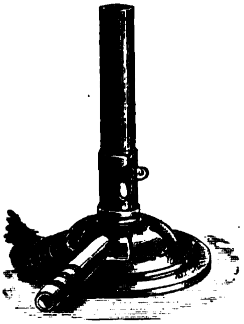


FIG. 52.—BUNSEN BURNER.

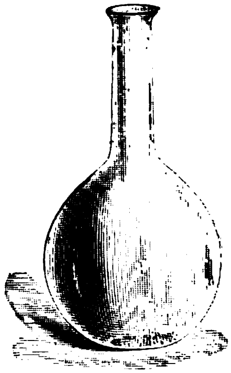


FIG. 53.—CHEMICAL FLASK.

Potassium cyanide (98 per cent.), 4 oz. = 113·39 grammes.

Water, 1 gal. = 4·542 litres.

PREPARATION OF THE SOLUTION.

The metal is put into a chemical flask (Fig. 53) covered with water (preferably distilled), some nitric acid added, and heated over a Bunsen burner (Fig. 52) until the metal is attacked. The flask should be held in the hand and constantly shaken whilst over the flame, acid being added only in small quantities, and then applied so as to keep up a fairly vigorous action on the metal. Boiling up too fast or too great a quantity of acid at a time, besides filling the place with deleterious nitrous oxide fumes, wastes the acid.

This heating, with addition of acid as

the action subsides, is continued until all the metal is dissolved, when a final boiling is given to drive off any excess of acid there may be. This boiling can be continued until the solution becomes syrupy, giving off dense white fumes. In this stage, on cooling, silver nitrate crystals will be formed. It is not necessary to carry this boiling so far when the bulk of the excess acid has been driven off. The dissolved silver is poured into a large flask or bottle, with abundance of water (not less than a pint to every ounce of metal).

In a separate flask is made up a 25 per cent. solution of 98 per cent. potassium cyanide, and this is added to the silver nitrate solution in small quantities, with vigorous shaking after each addition, until no more precipitate is formed on the addition of fresh cyanide. Towards the end (*i.e.* when the silver is nearly all down) of this operation great care is needed not to add an excess of cyanide, as the precipitate of silver cyanide would be redissolved and thrown away with the wash waters. Before making fresh additions of cyanide, the white flocculent precipitate should be allowed to subside, and then a drop of cyanide made to fall into the clear supernatant liquor, when the volume of precipitate produced indicates the condition of the liquid. If only a slight cloudiness is produced, no more addition should be made, as a vigorous shaking will throw down all remaining traces of silver.

The precipitate is allowed to subside, and the clear liquor decanted off into another vessel. Any remaining traces of silver it may contain can be thrown down by the addition of hydrochloric acid. This first decantation is called the "mother liquor."

The vessel containing the precipitate is filled with water and well shaken, the precipitate allowed to subside, and the clear liquor again decanted off. This is repeated three times so as to wash thoroughly the silver from all traces of nitrate of potash, the precipitate being finally left with water equivalent to a quart for every ounce of metal.

To this is now added some more of the cyanide solution in small quantities at a time, with shaking after each addition, and this is continued until all the precipitate is redissolved.

Finally, add to this as much of the cyanide solution as was required in all to precipitate and redissolve.

Roughly, in practice it can be taken that the same weight of 98 per cent. cyanide will be required to precipitate and redissolve as there is metal in solution, and half as much again should be added for the proper dissolution of the anodes.

The solution has finally to be aged by boiling, which, for large bulks, can be effected by passing steam through a lead pipe coil immersed in the bath.

Nearly the same thing is arrived at by passing a stiff current through the solution between two silver plates for five or six hours. The boiling is, however, preferable.

This method of preparing the solution is undoubtedly the best, the only troublesome part being the precipitation of the silver cyanide from the silver nitrate so as to add only sufficient cyanide to throw down all the metal without redissolving. To avoid this operation many platers precipitate the silver with hydrochloric acid (an excess of which does not redissolve the silver chloride formed, which is wasted and redissolved with cyanide as above). This method gives the disadvantages of an old solution without its compensation.

BRIGHT SILVER SOLUTION.

The bright silver-plating solution is the previous bath treated with bisulphide of carbon as follows. In a large glass-stoppered bottle are put half a pint of bisulphide of carbon, six pints of the plating solution, and two pints of 25 per cent. cyanide solution; they are shaken well up together and allowed to settle. For every 50 gallons of solution to be brightened, 4 to 6 oz. of the clear supernatant liquor of the above mixture is well stirred in (preferably overnight, when the bath is free from work, and allowed to rest till next morning). This has to be repeated from time to time as the condition of the deposit demands.

The bulk of the brightening solution can be kept up by replacing that which is used alternately with plating solution and cyanide solution, as long as bisulphide is left.

A silver solution once treated thus must always be kept in this condition, as it can never again be relied upon to deposit its metal uniformly as an ordinary bath.

The third silver solution that has to be spoken about is what is termed the striking bath. This will be given under the heading of auxiliary solutions, dips, etc., to which it properly belongs.

BRASSING SOLUTIONS.

These are employed for the intermediate coating of base metal, such as zinc, iron, etc., intended to be nickel or silver plated, or heavily coated with copper in the acid copper bath ; also, to be the finished coating for bronzing and decorative purposes generally. The writer uses this brassing as an intermediary in preference to the alkaline copper solution, whose only use is as a go-between. The deposit of brass seems more elastic than that obtained from the copper.

Of the possible brass solutions there are only two that need be considered here, and the only difference between these two is that one contains some ammonia, which is undoubtedly an advantage when such metals as zinc, pewter, etc., have to be coated. The formulæ for both are given ; but if the plant is only to allow of one brassing solution, preference should be given to the first, especially if iron and steel as well as the former metals have to be dealt with.

Preparation of one gallon of (No. 1) the brass bath :—

Zinc sulphate ...	4 oz. =	113·39 grammes.
Copper sulphate ...	4 oz. =	113·39 ,,
Carbonate of potash	8 oz. =	226·78 ,,
Cyanide of potassium (98 per cent.) ...	12 oz. =	341·3 ,,
Water	1 gal. =	4·542 litres.

The zinc and copper sulphates are dissolved together in a flask by heat in sufficient water, and then poured into a larger vessel with abundance of cold water.

In another flask is dissolved the carbonate of potash in the proportion of 5 oz. of salt to every pint of water.

This is added to the zinc and copper sulphates in small quantities at a time, with vigorous shaking or stirring after each addition, until no more precipitate is formed on the addition of fresh potash. Practically this will be when the same weight of potash has been added as there are zinc and copper sulphates in solution. The desired point is arrived at when the supernatant liquid (the precipitate having subsided) is colourless, and a drop of the potash does not produce a milkiness.

A too great excess of potash will dissolve some of the copper ; also, adding the potash in too great bulks without allowing it to disseminate gradually throughout the liquid has the same effect : this is shown by the clear liquid keeping its blue colour, which no addition of potash will cloud.

The zinc and copper carbonate is allowed to subside thoroughly, and as much as possible of the clear liquor decanted and syphoned off. Fresh water is added to the precipitate, which is well shaken up and allowed to subside. This wash water in its turn is decanted off, finally leaving the precipitate just covered with water. To this is added, in small quantities at a time, a 25 per cent. solution of cyanide, with a shaking up after each addition until the precipitate is redissolved ; then finally as much of the cyanide solution is added

M 10 U

as was required to dissolve the precipitate. The final result is a slightly turbid yellowish liquid, which should be boiled for some thirty minutes, filtered, and then made up to its intended bulk by the addition of water.

Preparation No 2. Double cyanides of ammonia and zinc and of ammonia and copper:—

Zinc sulphate ...	4 oz. = 113·39 grammes.
Copper sulphate ...	4 oz. = 113·39 ,,
Carbonate of potash	8 oz. = 226·78 ,,
Liquor ammoniæ (·880)	12 oz. = 316·75 cubic cent.
Potassium cyanide (98 per cent.)... ...	12 oz. = 341·3 grammes.
Water	1 gal. = 4·542 litres.

The zinc and copper sulphates are converted into carbonates and washed in the same manner as in the previous solution, but, instead of being dissolved with cyanide, liquor ammonia is added in small quantities at a time, with shaking after each addition. This is continued until all the precipitate is dissolved, resulting in a clear dark blue liquid free from sediment.

To this is added a 25 per cent. solution of cyanide, with shaking, until the blue colour disappears, resulting in a slightly yellow liquid, to which is then added as much of the cyanide as was required to decolorise. Finally, boil for some thirty minutes, then filter, and add water to the intended bulk.

COPPER SOLUTIONS.

Preparation of the alkaline coppering solution:—

Copper sulphate ...	8 oz. = 226·78 grammes.
Carbonate of potash	8 oz. = 226·78 ,,
Potassium cyanide (98 per cent.)... ...	12 oz. = 341·3 ,,
Water to make ...	1 gal. = 4·543 litres.

The copper sulphate is dissolved in sufficient hot water, and then poured into an abundance of cold water.

The carbonate of potash, dissolved in hot water and made up to a 25 per cent. solution, is added to the copper sulphate solution in small quantities at a time, and is vigorously shaken after each addition. The operation is continued as long as a precipitate is formed by the addition of fresh potash to the clear supernatant liquid. When all the metal in solution has been thrown down, the precipitate of copper carbonate is allowed to subside, and as much as possible of the colourless supernatant liquor is decanted or syphoned off.

Cyanide of potassium, dissolved by heat and made up to a 25 per cent. solution, is added to the above in small quantities (with vigorous shaking after each addition) until all the copper carbonate is dissolved; next, as much cyanide is then added as was required to redissolve. Finally, boiling, filtering, and making up to the intended bulk by addition of water gives the required solution.

Preparation of the acid copper solution:—

Copper sulphate	2·5 lb. = 921·3425 grammes.
Sulphuric acid (commercial) ...	10 oz. = 283·96 c.c.
Water	1 gal. = 4·542 litres.

The copper sulphate crystals, tied up in canvas bags, are suspended just immersed in boiling water contained in an earthenware vessel, fresh bags of crystals being added as long as they readily dissolve. When the liquid is saturated, it is to be filtered through a calico filter, supported on a wooden frame, into the tank intended to contain the copper bath, and the proper proportion of water added for the quantity of salt dissolved, the above routine being repeated until the desired bulk of solution is arrived at, finally adding the proper proportion of sulphuric acid, well stirring in the same.

The saturation of water at ordinary temperatures with copper sulphate is at about 50 oz. per gallon.

The above solution is the typing bath, but is also employed for thickening up the protective or intermediate coating of brass or copper on iron and steel goods intended to be plated or nickeled.

NICKEL SOLUTION.

Preparation :—

Ammonia and nickel doublesulphate	14 oz. = 396·88 grammes.
Water	1 gal. = 4·542 litres.

The ammonia nickel sulphate salt is tied up in paperhangers' canvas bags (about 2 lb. parcels), and suspended from a rod over an earthenware vessel containing boiling water, bags of the salt being added as long as it dissolves. When the water is saturated it is to be passed through a calico filter supported on a wooden frame over the intended containing tank for the nickel solution, and water added to make up to the proper contents of the bath for the salt dissolved. More boiling water is then put into the earthenware vessel, and the canvas bags refilled with the salt. The above operations are repeated until the desired quantity of the salt has been dissolved.

A stiff current is then passed through the solution between two nickel plates for five or six hours, after which it should be tested with litmus paper. If it turns blue paper violently red, some ammonia liquor should be thoroughly stirred in until the blue paper just slightly colours red; on the other hand, if red paper colours blue, dilute sulphuric acid should be stirred in until the desired result is obtained—viz. blue paper slightly reddens, indicating a slightly acid condition of the solution.

As a guide for the above preparation, water at ordinary temperature may be considered saturated with the above nickel salt when it has taken up 20 oz. of salt per gallon.

GILDING SOLUTION.

For obtaining a good colour and deposit from this solution it is usually used warm, not less than 50° C. (122° F.), and is most readily contaminated by the work, immersed copper or silver work giving something of their base to the solution, resulting in a red or light deposit of gold.

For this reason small quantities of the solution are usually made up daily or as required for colouring purposes, and the residues of each day's solution go to make up and keep a solution in which work is given a preliminary coating of gold, to be finally coloured in the freshly prepared solution, thus saving the new bath from contact with base metals.

The solution used is the double cyanide of gold, usually prepared from the neutral chloride by dissolving this in water and shaking up with a piece of cyanide until the yellow colour disappears, and then immediately removing the cyanide. When heated up the solution is ready for use.

The quantity of gold per quart of bath can vary infinitely, it being possible to throw down the gold from solutions containing only traces of the metal. Two to four dwts. = 3·1 to 6·2 grammes, per quart of solution is a fair proportion.

AUXILIARY SOLUTIONS.

In these solutions are included the strips, pickling and bright acid dips, potash and cyanide dips, silver striking and quicking dip.

In mixing up the various pickles, etc., given below, it is necessary to start with the lightest liquid first, thus: water, nitric acid, then the sulphuric acid. Should the water be added to the sulphuric, ebullition would occur that may seriously injure the operator.

As in all other formulæ given in this portion of the work, the amounts of liquid materials are expressed by volume.

ACID PICKLES AND DIPS.

A good general pickle for copper and its alloys is composed as follows :—

Sulphuric acid (1·815 sp. g.) ...	1¾ gallons.
Nitric acid (1·420 sp. g.) ...	4¼ ,,
Common salt	1 oz.
Lampblack	1 oz.

The organic substance, such as the lampblack in the above mixture, is to obtain the presence of hyponitric acid, and the salt for obtaining some chlorine. This must be mixed in the open, and is only fit for use twenty-four hours afterwards.

A good bulk of acid must always be prepared, so that it may not get hot with use. If it is not kept cold, uniform results cannot be obtained. The above remarks apply to all acid pickles.

It is also to be remembered that acid dips do not remove grease. To do this, all work must be passed through the hot potash solution, rinsed, and given a scrubbing with pumice and water; then rinsed, and passed into the acid dip, in which it should only be allowed to remain a few seconds, with constant shaking. It is quickly removed, and with the least exposure to the air is swilled in a large volume of water (rinsing from the acid under the tap is not to be attempted). If it does not present an uniformly bright surface, it should be passed through the cyanide dip and given another scrubbing with the pumice powder, and again passed through the pickle. The operations must be repeated until the desired result is obtained.

Swilling in the cyanide dip after rinsing from the acid is in every case of pickling advisable, as not only does it kill any acid that may remain in the pores of the metal, but it prevents the rapid oxidisation on exposure to air to which pickled surfaces are liable.

For work made of copper and its alloys which are not intended to be plated or mechanically polished, but are pickled to brighten them for lacquering, etc., a solution composed as below must be kept specially for the purpose, and from it water must be rigorously excluded.

The bright dip has the following composition:—

Sulphuric acid (1·815 sp. g.) ...	1 gallon.
Nitric acid (1·420 sp. g.) ...	1 ,,
Common salt	2 oz.

The work, having gone through the routine of the preceding dip, and being as bright as that dip will make it, is swilled in boiling water, well shaken to dry, and then plunged in the above bright dip and rapidly shaken about for a second or two; on removal, it is instantly swilled in abundance of water, passed through the cyanide dip, rinsed in hot water, and finally dried in warm sawdust.

A soaking pickle—that is, a pickle to be used for rough castings or as a preliminary pickle for all work, to save the ordinary pickle—is composed as follows:—

Nitric acid (commercial)... ...	1 gallon.
Common salt	1 oz.
Lampblack	2 oz.

Castings are allowed to soak in this until all the scale is loosened, then rinsed in water, scrubbed with pumice powder, and passed through the ordinary or the bright dip.

An acid dip for producing dead or matt surfaces is composed as follows:—

Sulphuric acid (1·815 sp. g.) ...	4 pints.
Nitric acid (1·420 sp. g.)... ...	1 gallon.
Common salt	1 oz.
Zinc sulphate	¾ oz.

The zinc sulphate is dissolved in a little water and added to the mixed acid; it is upon the contents of this that the degree of pitting depends, as well as upon the length of time the work is immersed. The earthy appearance of the work from this pickle is removed by passing through the bright dip above.

A good pickle for cast iron, iron, steel, etc., is composed of:—

Sulphuric acid (1·815 sp. g.) ...	12 oz.
Nitric acid (1·420 sp. g.) ...	5 oz.
Sulphate of zinc...	2 oz.
Water	1 gallon.

The work is allowed to soak in this solution sufficiently long to loosen the scale, etc.; it should be removed from time to time, and given a good scrubbing with a stiff brush and pumice powder, and returned to the pickle. The process is repeated until a uniformly bright surface is obtained. Finally the casting is rinsed in water and passed through the hot potash to remove all traces of acid that may remain in the pores.

For zinc a 20 per cent. solution of sulphuric or hydrochloric acid is all that is required, and a plentiful scrubbing with pumice powder.

The cyanide dip consists of 1 lb. of good potassium cyanide to every gallon of water.

The quicking dip is prepared as follows. 1 oz. of mercury is put into a flask and covered with water, to which is added some nitric acid, and it is then heated over a Bunsen flame until the mercury is attacked. Acid is added from time to time as the action slows down, this being continued until all the mercury is dissolved, and the solution is left with a slight excess of nitric acid. This is then poured into a gallon of water, in which is dissolved 12 oz. of 98 per cent. potassium cyanide. The slight black precipitate which is formed is allowed to fall to the bottom, and it is gradually taken up.

The boiling potash consists of 1 lb. of American potash to every gallon of water contained in a steam-jacketed wrought-iron tank.

STRIKING SOLUTION.

Silver nitrate	1 oz.
Potassium cyanide (98 per cent.)	12 oz.
Water	1 gallon.

The silver is dissolved in water and poured into the water in which the proper proportion of cyanide has been dissolved. It is to be used warm at about 60° C. = 140° F., a strip of sheet iron being employed as anode.

STRIPPING AND STRIPPING SOLUTIONS.

By "stripping" is meant the removal of old coatings of deposited metal from work that has to be replated, either old coatings worn or defective new work.

This may be effected chemically or mechanically, the solutions for the chemical processes depending entirely upon the basis metal (*i.e.* the metal of which the object is made), as it is requisite that this should be inert in a solution that attacks the coating to be removed.

For work that has not too great intricacies a mechanical stripping can be advantageously employed, especially as it is necessary to sand before plating all work that has to have a finished surface, the one operation being employed to effect both purposes. In the latter case (when grinding plated work) a bag of sand is kept specially, from which the metal can be recovered.

For chemically stripping silver from copper and its alloys, the fuming sulphuric acid (*i.e.* acid free from water), with a small quantity of nitric acid, is employed, either hot or cold. If time is not a consideration, the latter is preferable, as it effects its purpose more regularly, with less danger of attacking the basis metal than when employed hot.

For cold solutions equal parts of anhydrous sulphuric acid and 1·420 nitric acid make a solution very suitable for the purpose.

When used hot, the sulphuric acid should be put into an enamelled cast-iron pot and heated to about 300° F. = 150° C., into which (just before immersion of the work) small quantities of dry nitrate of potash (powdered) are thrown and stirred up, this potash being added until the silver is attacked, after which only just sufficient should be thrown in to keep up the action. Moving the work about makes the attack more uniform, and it also washes away the loosened silver from the surface. It is generally possible to see when all the silver has been dissolved without removing the work from the solution. When freed from all traces of silver it is removed from the solution and plunged into the bright dipping acid, and immediately swilled in abundance of water; if there is any silver left on any part of the work, it will show up in brownish dark spots, necessitating a return to the "strip;" but before this is done it must be thoroughly dried, as no moisture whatever must be allowed to enter the strip; also for this reason the solution must (when not in use) be kept in well-stoppered glass bottles.

Note.—The work before immersion in the strip should be freed from all grease by being boiled in potash and scrubbed with pumice, rinsed in water, and dried by swilling in boiling water and shaking the latter off.

For removing silver from iron or steel goods the following is a simple method which is available, owing to the fact that these metals are not attacked when used as anode in a cyanide solution. All that is required is a solution of potassium cyanide, containing half a pound of salt to a gallon of water. The work to be stripped is immersed and attached to the positive pole of the dynamo or battery; for cathode a silver anode or a piece of iodised copper sheet can be used—in the latter case the silver deposited is separated from its basis when sufficiently thick and used as an anode in the silver solution. A good stiff current being employed, the work is soon stripped.

NICKEL STRIPPING SOLUTION.

For removing old or defective coatings of nickel a solution of the following composition is employed:—

Sulphuric acid (1·815 sp. g.)	...	1 gallon.
Nitric acid (1·420 sp. g.)	...	2 pints.
Water	...	3 ,,

The work to be stripped, having been freed from grease, is suspended by means of copper wires in the above solution, and should be constantly moved about so as to detach the loosened nickel, as it is requisite that the work should not remain longer immersed than is absolutely necessary for denickeling.

FOR STRIPPING GOLD FROM GILDED WORK.

To strip gilding from silver and alloys of copper a dip of the following composition is employed: to every 2 pints of sulphuric acid (1·815 sp. g.) are added 3 oz. of hydrochloric acid and 1½ oz. of nitric acid (1·420 sp. g.). This solution, as is the case with the silver strip, must be kept free from contamination with water, and when not in use should be kept in glass-stoppered bottles.

The work, which must be dry, is suspended by a copper wire and shaken about in the above solution, which should be used at about 60° C. = 140° F., careful watch being kept so as to remove the articles immediately all traces of gold have disappeared.

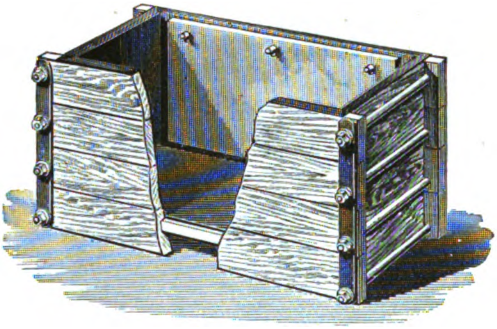


FIG. 54.—LEAD-LINED WOODEN PLATING VAT.

For removing gold from iron and steel goods resort is made to the electrolytic method, the work being made anode in a solution containing 1 lb. of potassium cyanide to the gallon, using a strip of copper sheet as cathode.

CONTAINING TANKS, VATS, ETC.

The containing tank or vat for the acid copper bath for sizes over 30 gallons should be made of wood, lead lined; for sizes up to 200 gallons a wood tank made of $1\frac{1}{2}''$ deal, bolted at the ends, and lined with 5 lb. lead sheet, dressed over the top edges of the wood as shown in Fig. 54. The inner protective lining can be made of cast glass sheet $\frac{1}{4}''$ to $\frac{3}{8}''$ thick, cut to the size of the inner sides of the tank, and kept in position by a rabbeted strip of wood fixed to top of tank over the lead. Or in place of the glass, sheets of vulcanised rubber (ebonite) $\frac{1}{8}''$ thick can be hung on pegs at the top of the tank to correspond to bayonet slots cut in the ebonite.

Lead-lined wooden tanks like the above also serve as vats for the silver bath, brass bath, nickel, etc., for bulks exceeding 500 gallons; for smaller quantities than this, slate tanks, as shown in Fig. 55, are recommended.

These are made of Bangor slate for capacities up to about 100 gallons; slabs 1″ thick.

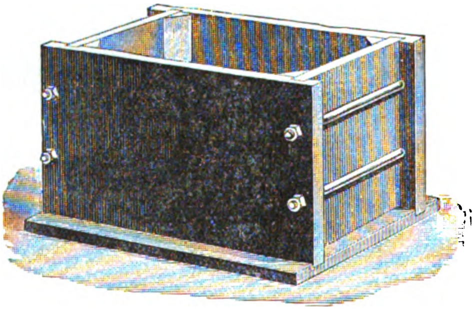


FIG. 55.—SLATE PLATING VAT.

From this up to 500 gallons the wall should be $1\frac{1}{4}''$ thick; they are grooved and bolted as shown, and should be jointed up only in position, as it is not advisable to shift them when put together. The jointing material is red lead, which should be allowed to harden for ten days or so before use.

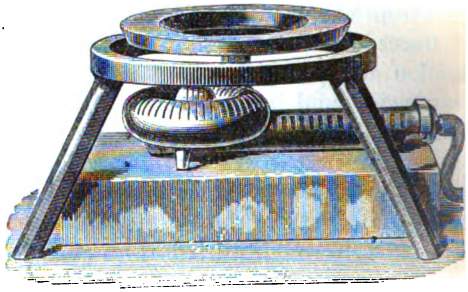


FIG. 56.—TRIPOD AND BURNER FOR HOT GILDING PAN.

This is then protected from the action of the electrolyte by covering the seams inside

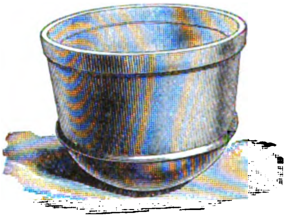


FIG. 57.—PAN FOR WARM GILDING SOLUTION.

with Portland cement, mixed with one-third white sand, and applied as quickly

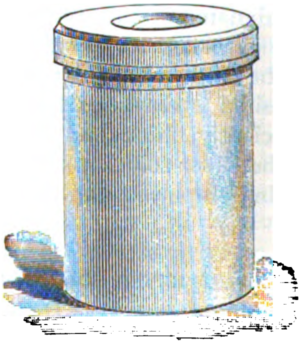


FIG. 58.—JAR FOR STRONG ACID PICKLING SOLUTIONS.

as possible after mixing. It is placed round the four bottom seams and four upright corner seams, so as to chamfer off the angles (see Fig. 55).

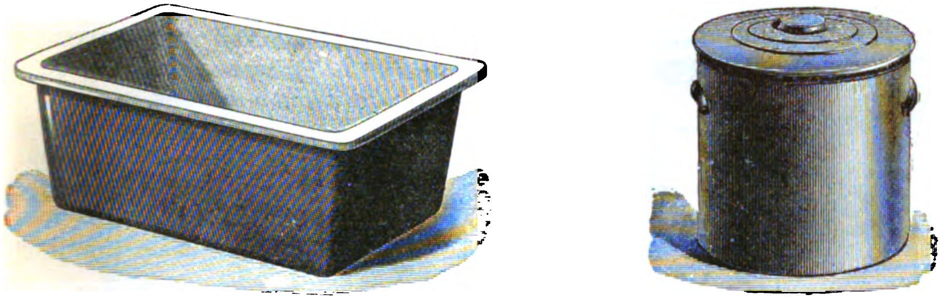


FIG. 59.—IRON SWILLING TROUGH AND COVERED PAN FOR CYANIDE DIP, ETC.

These slate tanks are suitable for the following solutions (used cold): Silver cyanide, brassing solution, alkaline copper, cobalt and nickel solution, steel-facing solution, etc.

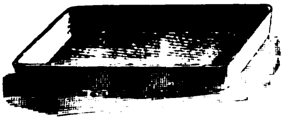


FIG. 60.—OPEN PAN FOR SMALL WORK.

For the warm gilding solutions earthenware boilers (biscuit ware) glazed inside having a flange at the bottom to stand on a tripod, as shown in Fig. 56 and 57, and heated with a Bunsen ring. These are also very good for small bulks of quicking solutions.

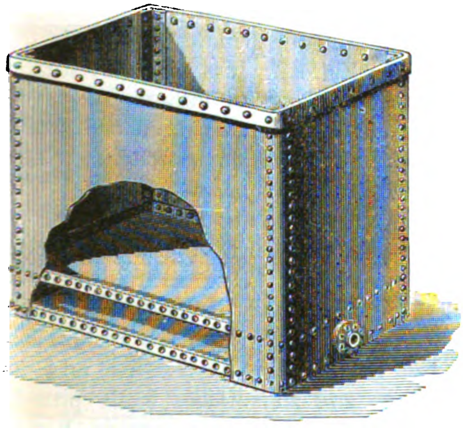


FIG 61.—STEAM-HEATED TANK FOR HOT POTASH DIP.

For small bulks of solutions earthenware or glass pans are suitable.

All the strong acid pickles should be kept in vitrified stoneware jars, the shut-over jars, for bulks up to 6 gallons, and the retorts supported in strong wooden frames for larger bulks.

The wash waters can be held in the open pans shown for small work (Fig. 60). Paraffin oil barrels cut in half and scoured out make good swilling troughs for larger bulks.

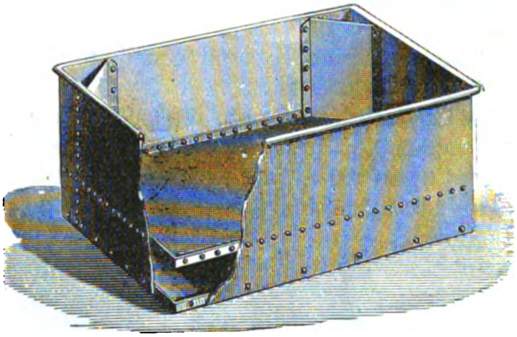


FIG. 62.—CAST-IRON STEAM-HEATED TANK FOR HOT DIP.

The cyanide and mercury dips can also be kept in these pans supplied with a wooden cover, or glazed bread pans with covers are available up to any size.

The boiling potash is kept in iron tanks, strongly riveted and caulked, as galvanising is not to be relied upon to make good defective joints. If steam is available, they should be provided with false bottoms, as shown in Fig. 61, having inlet and outlet flange and flat band round the top up to 400 gallons. Ten-gauge plate can be used with not less than $\frac{3}{16}$ plate for the top of false bottom.

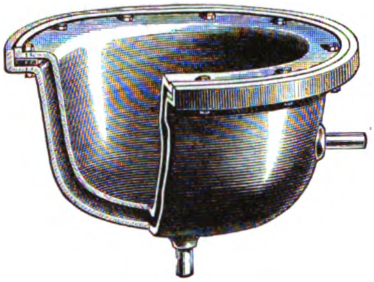


FIG. 63.—STEAM-HEATED ENAMELLED POT FOR STRIKING DIP.

If the potash has to be heated with gas, lighter tanks without the false bottom can be used.

The remarks above apply equally to the boiling-water container.

A cast-iron kettle up to 110 gallons may be obtained, with steam circulating space tested up to 200 lb. pressure, which has the great advantage of no joints. A tank of this order, 45″ × 24″ × 24″ inside, costs about £15. It is shown in Fig. 62.

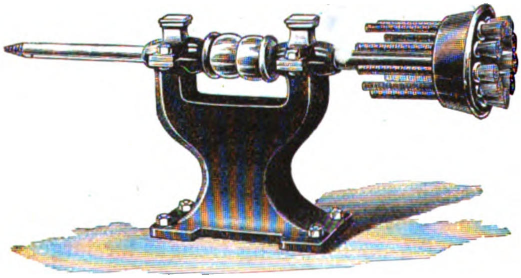


FIG. 64.—GRINDING AND POLISHING SPINDLE-POWER DRIVEN.

For the striking dip is required a rectangular or round cast-iron enamelled pot (Fig. 63), with or without steam space, depending upon the heating being by gas or steam.

APPARATUS REQUIRED FOR THE MECHANICAL PREPARATION OF METAL SURFACES TO RECEIVE A DEPOSIT.

As before stated, if work when plated is to have a finished surface, that surface must be given to it before the coating in the electrolytic vat. All scratches and irregularities of surfaces, file marks, pittings through brazing, cast surfaces, etc., must be ground out, and the surface brought to that texture which is called "sanded"—that surface given by the use of Trent sand employed with leather bobs or discs revolving at great speed.

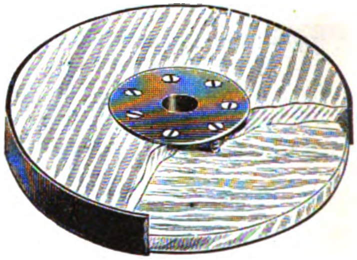


FIG. 65.—BOB FOR GRINDING CAST IRON, ETC.

A polishing or grinding spindle is illustrated in Fig. 64. It is driven by steam at 2,000 revolutions per minute, and carries taper screws for driving the bobs and mops, also plates for clamping and driving emery discs and large-size mops and bobs.

They should be driven from a shaft running under the bench upon which they are fixed, the bench being strutted to a wall of the shop so that the application of work to the spindle will stiffen the arrangement.

For the grinding of cast-iron and brass surfaces, and all surfaces badly pitted or cut, bobs, like that shown in Fig. 65, charged with emery of various grades depending on the hardness of the metal being ground, are made and used as follows. Two or more pieces (depending on the width of face required) of ½″ pine or poplar wood are planed true and well glued together, with their grain at right angles to each other. In gluing up for large bobs both wood and glue should be made hot and squeezed up under a hydraulic press until cold, after which a few dowel pins should be driven in. A hole large enough to pass the end of the spindle is bored in the centre and faced on both sides with brass or iron washers, secured in place by screws. It is then clamped in place on the spindle and turned true all over. Small wheels need only have a taper hole drilled in the centre sufficiently large to take the taper screw on the spindle.

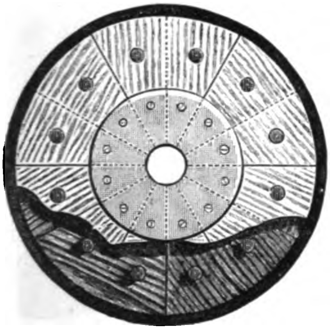


FIG. 66.—GRINDING BOB BUILT UP IN SEGMENTS.

Another way to make these wood bobs is to join the wood up radially, as in Fig. 66, the width of face being made up in two thicknesses, so that the joins on one side are in the centre of the piece on the other side, the whole being clamped with two bosses of wood or metal screwed into each segment, a dowel pin being driven into each segment, then screwed on the spindle, and the sides and periphery turned true. This undoubtedly gives a bob with a more uniform surface to its periphery, and will keep more truly circular. As regards true running it has been said that only small bobs, etc., are to be driven by means of the taper screw on the spindle. For large sizes a hole true to the spindle must be bored, and the bobs, etc., strongly clamped by means of the plates. These bobs run from 1″ wide to 4″ wide on the face, and from 8″ to 30″ diameter, so that a point on the periphery of the largest bob travels about 15,000 feet per minute. If it is in the least out of truth, it will set up great vibrations which are liable to shake the machine to pieces if not actually to break the spindle; this is graphically expressed by saying that "to save the spindle travelling round the shop it must run true."

On these wooden bobs is glued good oak-tanned bull-neck leather, a strip being cut the width of the bob and of sufficient length. This is soaked in water till very pliable, and a coating of good glue given on the under side; then fixed in position on the periphery of the wooden bob, and further secured by small dowels of soft wood driven below the surface of the leather. When thoroughly dry it is placed in position on the spindle, and the surface of the leather turned true.

Bobs made as above, if used for grinding, are coated with emery powder; if for polishing, they are used with sand and Sheffield lime.

For grinding bobs they are coated with various grades of emery, three sizes being usual, those coated with No. 10 emery being termed the roughing wheel, No. 54 the medium wheel, and those coated with No. 180 the fine wheel.

Charging the bobs is effected by giving to the surface of the leather a good coating of glue, and then rolling them with pressure in the dry emery powder. The finer emeries can be mixed with the glue, a coating of the mixture given, and then rolled in the dry emery of the same grade.

The work is presented to these bobs with not more than sufficient pressure to make them cut. They are used dry unless they are found to drag, when they must be moistened with oil, charged with some of the same grade emery as the bob in use.

For work that has an uneven surface which the bobs will not reach, bristle brushes charged with oil and the requisite grade of emery can be used.

Rounded, knife-edged, and miniature emery bobs are cut out of the solid leather, mounted on the spindle, turned to the desired shape, and charged with emery in the same way as the wood-covered ones. According to the thickness required, they are cut out of bull-neck, walrus, or sea-horse hide—the latter running to quite 1" thick. These solid leather bobs have a springiness which gives a grand cutting effect.

Two other sets of the above bobs are also required, not surfaced with emery, for use with sand and lime ; also colouring dollies or buffs. These are simply a number of discs of swansdown calico, which (home made) are threaded on a spindle and held together by two leather washers, one on either side, fastened through with wire nails ; the taper screw of the spindle passing through the two leather washers gives sufficient hold to drive. For large diameters they are preferably sewn up to two or three inches of the periphery and clamped between the plates. A coarser cutting buff is made in the same manner as above, using unbleached calico in place of the woollen cloth.

The material for use with these bobs, etc., is Trent or Calais sand, which is to be mixed with just sufficient oil to make it bind when squeezed in the hand.

Sheffield lime should be treated in the same way as above. The stock of this must be kept in well closed tins, or it will take up carbonic acid and moisture from the air and become useless for cutting purposes.

Crocus and rouge mixed with wax and oil, made into sticks by pressure, are used to charge the felt and calico dollies for colouring, etc.

The operations of grinding and polishing consist in presenting the surfaces to be worked upon against the periphery of the various bobs, etc., with sufficient pressure, and in moving them backwards and forwards in all directions. Skill is required to grind equally all over, as if more is taken away in one place than another the surface has a wavy appearance quite fatal to good work. The skill of the operator is shown on large flat sheets of metal and on spheres, etc.

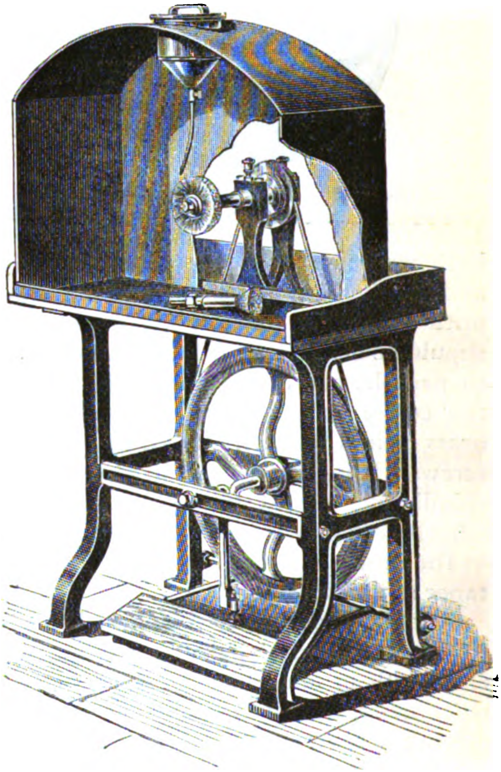


FIG. 67.—FOOT-DRIVEN SCRATCH BRUSH SPINDLE ON STAND.

In sanding or colouring with lime the bob must be kept constantly charged with the cutting material. This is effected by keeping the left hand filled with the sand or lime, and supporting the work in this as near to that portion directly under operation as the condition of the operator's

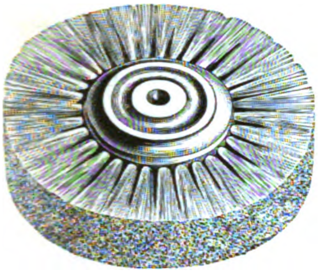


Fig. 68.

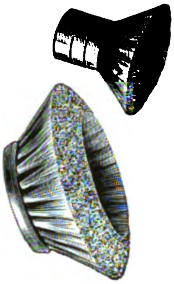


Fig. 69.

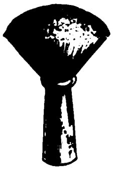


Fig. 70.

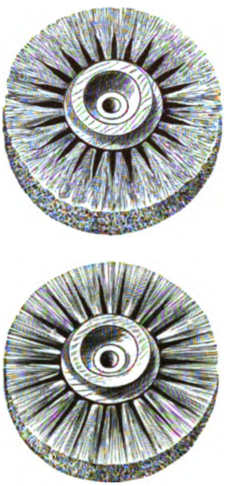


Fig. 71.

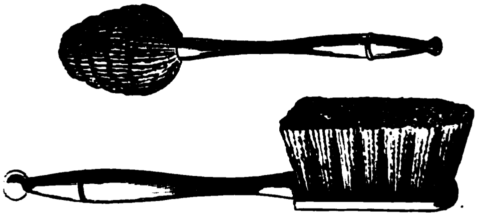


Fig. 76.

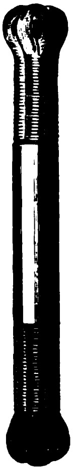


Fig. 75.

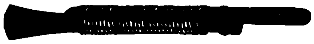


Fig. 73.

Fig. 72.

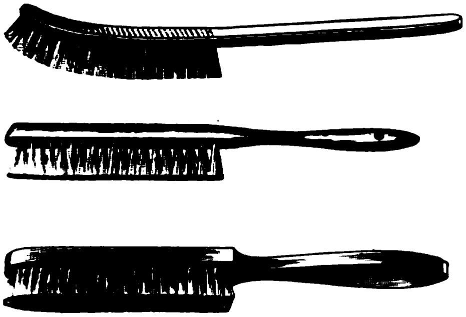


Fig 74.

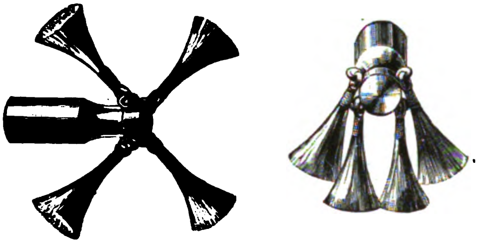


Fig. 77.

FIG. 68.—ORDINARY SCRATCH BRUSH. FIG. 69.—CUP-SHAPED SCRATCH BRUSHES. FIG. 70.—DOME-SHAPED SCRATCH BRUSH FOR TAPER-ENDED SPINDLE. FIG. 71.—FINE AND COARSE SCRATCH BRUSHES. FIG. 72.—WIRE READY FOR INSERTION IN SCRATCH BRUSH. FIG. 73.—HAND SCRATCH BRUSH. FIG. 74.—HAND SCOURING BRUSHES. FIG. 75.—HANK OF WIRE FOR MAKING SCRATCH BRUSH. FIG. 76.—HAND SCRATCH BRUSHES. FIG. 77.—KNOT SCRATCH BRUSHES FOR USE WITH POWER DRIVING.

hand will allow, so that the lime, etc., may be drawn in between the work and the bob.

Rubbing away at an uncharged bob is waste of time.

For polishing hard steel surfaces the coarse emery bob, or for rough cast-steel surfaces solid emery and corundum wheels are used to rough out; then medium ones to remove the coarse scratches left from the preceding wheel, and so on down to the lime bob and colouring dolly, always remembering that the work must be presented to the bobs in every possible direction.

Brass and similar castings can be roughed out on the roughing wheel and brought down to the sand and lime bobs, finishing up on the calico dolly; this being charged by holding, for a second, a piece of lime against the revolving disc, and smearing a little oil on the work, finally bringing it away when quite dry.

For ordinary manufactured work and new metal, sanding and finishing off with the lime bobs and dollies is usually sufficient; at most a worn-out fine emery bob will be required for deep scratches.

For zinc castings with designs use a bristle brush charged with fine emery and oil; for smooth surfaces lime bobs and colouring dollies.

For colouring silver-plated ware, use the calico dolly charged with crocus, finishing with the swansdown mop charged with rouge.

In all cases the use of too much oil with the various polishing materials must be avoided, as it causes smearing and prevents cutting.

Further mechanical treatment necessary for proper electro-deposition is supplied by the scratch brush. A scratch brush lathe or spindle is shown in Fig. 67; it is the same as the polishing spindle, but not necessarily so heavy, and must be provided with a hood to catch the splashing caused by the lubricant falling upon the rapidly revolving brush.

On the top of the hood is placed a bucket with a short length of pipe (provided with a tap) passing through a hole in the hood. Beneath the spindle is a tray capable of holding water, and having a spigot by which the lubricant can be drawn off and returned to the bucket at the top. A miniature centrifugal pump similar to those used on emery grinding wheels may be used to pump the liquid caught by the tray back into the bucket, or through a rubber tube to a nozzle which can be placed at will in any position over the brushes. To prevent dirt, etc., getting into the pump, the tray has an overflow tube, so that the pump deals only with the liquid skimmed off the top.

The brushes are made of hard-drawn brass wire of different gauges, depending on the hardness of the metal to be operated upon: for brass, copper, zinc, etc., about No. 35 S.W.G., for silver about 38 S.W.G., and for gold about 42 S.W.G., will be the sizes most useful. Brushes are made in all diameters, and widths to one, two, three, or four rows, as the work requires; and brushes are also made hollow, or cup-shaped, and dome-shaped, to reach the bottoms of tankards, and the inside seams of rectangular work, etc. etc. Steel-wire brushes are also in use for scratch brushing nickel-plated castings, etc.

Work must be scratch brushed with a plentiful supply of lubricant, and must not be pressed too heavily against the brushes. The ends of the wires travelling at a high speed do the work, too hard pressure only ruins and breaks off the wires. The scratch knots illustrated on the spindle in Fig. 64, are simply hanks of wire folded in half and bound tightly round the middle, with soft brass wire about No. 20, leaving about 1″ free each end, the ends being cut as shown in the illustration. A number placed in position in grooves on a taper wooden chuck, and kept in place by a brass hoop tightly driven over, makes, on a steam-driven spindle, a good stiff brush for washing out the sand, etc., from pores and castings that have been pickled, the stiffness of the brush depending on the length of the brass knots that are allowed to project. Various forms of scratch brush, for power or hand use, are illustrated in Figs. 68-77. For hand scratch brushing the knot is held with extended fingers low down, and, the elbow being kept high, the pieces are repeatedly struck, soapy water or beer being used plentifully as a lubricant.

CHAPTER III.—PLATING WITH SILVER AND NICKEL.

SILVER ON COPPER AND ITS ALLOYS—SILVER ON ZINC—SILVER ON BRITANNIA METAL, PEWTER, ETC.—SILVER ON POLISHED IRON—SILVER ON CAST IRON—NICKEL ON COPPER—NICKEL ON CASTINGS—NICKEL ON WROUGHT WORK—NICKEL ON ZINC—FINISHING AND COLOURING—MANAGEMENT AND ESTIMATION OF SOLUTIONS—SUSPENSION OF ANODES.

SILVER-PLATING COPPER AND ITS ALLOYS.

This work is brought up to the sanded surface in the polishing process—that is, deep scratches, pits, etc., are ground out with well-worn emery bobs (those made with solid leather being preferable for this work), the surface being afterwards treated all over with the sand until all roughness of the previous treatment is removed, so as to obtain a perfectly uniform surface of the texture given by the sand. In this condition the work is said to be sanded, and is ready for the chemical cleansing preparatory to its immersion in the depositing vat.

For intricate work—that is, work which holds considerable quantities of the greasy sand used in polishing—a brushing out in mineral naphtha to remove all this from the crevices, etc., is the first operation, with subsequent drying out in leather shavings (that obtained from turning up the various bobs being kept for this purpose).

Work that does not require this preliminary washing out can immediately be immersed in the boiling potash by slinging with copper wire on a rod placed over the containing tank.

The immersion here is for four or five minutes, with, if necessary, a brushing with the cotton brushes used for this purpose.

On removal from this, it is swilled in water and shaken in the cyanide dip, then put on the bench in the scouring trough and given a good brushing all over in every direction. For this bristle brushes are used, plentifully charged with medium grain pumice powder made into a paste with some cyanide solution.

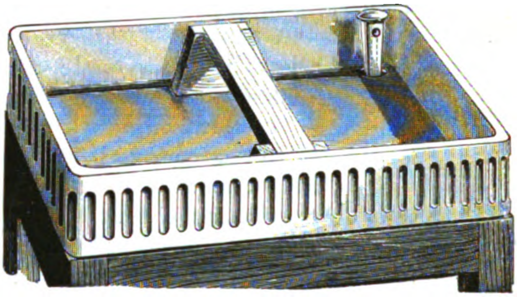


FIG. 78.—SCOURING TROUGH AND BENCH.

This, which is the important part of the operation, having been thoroughly effected, the work is swilled in water; then shaken for a few seconds in the cyanide dip; next for a few seconds in the quicking dip, from which (if the cleaning has been effective) it should emerge perfectly white without any dark stains. If this is the case, it can be rinsed in abundance of water and immediately immersed in the plating vat through which the current should be already passing.

Should the quicking not turn out perfectly uniform, the work must be scoured again with the pumice and cyanide, swilled in water, and then taken to the bath.

A very effective procedure is to suspend it in a fairly strong cyanide solution for some five or ten minutes after rinsing from the quicking. From the cyanide it will generally emerge beautifully white; but in any case it is always as well to give a final scrubbing with the pumice before immersion in the vat.

There should be a separate cyanide dip for this soaking of the quicked work as it gradually becomes charged with mercury. When too loaded it must be renewed.

The scouring trough is preferably a large glazed earthenware sink as supplied by Stiff or Doulton, having an overflow plug, as shown in Fig. 78, and a tap immediately above it for a plentiful supply of water. The scrubbing bench should be supplied with a pad, made of three or four thicknesses of house flannel.

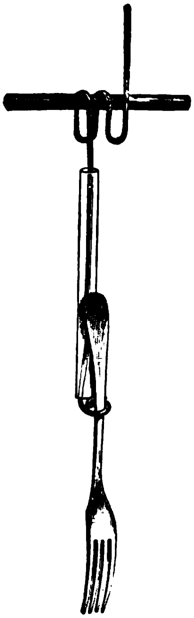


FIG. 79.—MODE OF SLINGING A FORK IN THE PLATING BATH.

The pumice paste, cyanide dips, quicking, etc., should all be quite handy to the scouring bench.

The work during the process of chemical cleaning should not be handled more than necessary, and only with hands that are kept constantly charged with pumice and cyanide; also in passing it from dip to dip, etc., it should not be allowed to see the air more than is absolutely necessary.

Some ten minutes after immersion in the depositing vat, when the work has received a blush of silver all over, it is removed, rinsed, and given a good scratch brushing; this will show whether there is a good adherence of the deposit to its base, besides making it more homogeneous, the metal being deposited in a granulated state, which this scratch brushing smooths down. After scratch brushing it, swill it in cyanide, brush it all over with the cyanide pumice paste, and return it to the bath.

This scratch-brushing may be repeated with advantage several times during the process of thickening the deposit.

Work should always be slung in the bath in such a manner so as to alter its position easily in the solution, to shield it least from the anode, and to have as little of the slinging wire immersed as possible, so as to avoid depositing metal uselessly.

Forks, spoons, etc., can be conveniently slung with a hook made of No. 16 copper wire, enabling the spoons, etc., to hang perpendicularly in the bath, to be readily reversed in position, and shielding as little as possible of the work. As shown in Fig. 79, there is a spring loop at bottom, with a double hook at top, preventing swinging about of the work. If desired, the stem can be covered with glass or rubber tube before making the hook, so as to save the waste of deposit.

Work must be hung in the solution so that no portion of it is shielded by other work. Always let it face square on to the anodes, which should surround it; failing which, all faces of the work should in turn take up the most advantageous position relative to them.

There should be not less than 4″ between the anodes and the work, and for very irregular work with deep pits, etc., 8″ or 10″ should separate them.

Proper current densities and management of solutions are given in the following chapters.

For castings of copper, brass, etc., the operations should follow one another thus: A sufficiently long soaking in the pickling dip to loosen the scale and oxide from every part; then a rinsing in water and a good scratch brushing with a steel wire brush or very stiff brass brush to remove all the loosened sand, etc.; after which, a good brushing with the pumice and cyanide; then a rinsing, and an immersion for an instant or two, with shaking, in the general acid dip, on removal from which an instant plunge in abundance of water and a thorough rinsing. If the work emerges from this of a uniform brightness, it is passed through the cyanide dip into the quicking dip, given a brushing with the pumice, and immersed in the plating solution. If a uniform surface is not obtained with the first immersion in the acid dip, another scrubbing with pumice and immersion in the acid must be given.

SILVER-PLATING ZINC.

For silver-plating smooth zinc work, commence with a polishing with leather bobs and sand, and bring the work to a finer surface with Sheffield lime, etc.

For cast zinc work with designs and raised decorative work, give a good brushing with the steam-driven circular bristle brushes, plentifully charged with flour of emery made into a paste with oil; after this brush it out with mineral naphtha, and dry with leather shavings. This constitutes the mechanical preparation of this metal.

The chemical cleansing consists of a few seconds' immersion in the boiling potash, followed by a rinsing and a passing through the cyanide dip; next, a scrubbing with the cyanide pumice powder paste, which must be done thoroughly; then a rinsing in abundance of water and an immersion in the brassing solution, through which a current should be passing immediately on immersion of the work.

For intricate zinc castings, parts of which the scrubbing brush does not reach, a passage through the pickle given for zinc is advisable; after being well swilled from this, it is passed through the cyanide dip and given another good scrubbing with the pumice powder before immersion in the brassing solution.

Ten minutes or so after immersion in the brass bath (when the work should be coated all over with a deposit of brass), it is removed, rinsed in water, and given a thoroughly good, vigorous scratch brushing all over and in every direction; and if there are any parts from which the brass is removed, they must be particularly attended to in the subsequent passage through the cyanide dip, and by scrubbing with the pumice before being returned to the bath. They are then allowed to remain for about sixty minutes, with an occasional alteration of position, and at least one more scratch brushing, with its attendant scouring with pumice, during the hour.

On the final removal from the bath a rinsing and scratch brushing is given, after which a passage through the quicking solution; then a rinsing and brushing with the pumice-powder paste, and a rinsing in abundance of water; it is then immediately immersed in the silver-plating vat, through which the current should be already passing. When it has received a blush of silver all over, it is removed, rinsed in water, and given another scratch brushing, with its attendant brushing with the pumice, and returned to the bath to complete its coating.

The details of attention in the bath are the same as those given for the previous metal.

SILVER-PLATING ALLOYS OF ZINC, SUCH AS BRITANNIA METAL, PEWTER, ETC. ETC.

These metals are to be given a few seconds in the boiling potash, after which a good scouring with the pumice-powder paste, then rinsed in water, and given a good scratch brushing; after this a slight brushing again with the pumice, and immersion in the boiling potash sufficiently long to bring it to the same temperature as the potash, from which it should be taken and instantly plunged into the hot striking dip (the cathode wire being attached whilst immersing), and a strong current allowed to pass for a few seconds. For hollow ware a strip of iron sheet attached to the anode by a flexible wire is held inside the work. A few seconds in this strike is all that is necessary; on removal from it a rinsing is given, and then a good scratch brushing, finishing up with a passage through the cyanide dip and a brushing with the pumice-cyanide paste, with immediate immersion in the silver-plating solution; the necessary attention here being the same as for the previous examples.

SILVER-PLATING POLISHED IRON AND STEEL.

After the grinding and polishing, the work is immersed in boiling potash for a few minutes to remove grease, etc., and then given a good scouring with pumice paste, and returned for a few seconds to the boiling potash, from which (without allowing to cool) it is immediately plunged into a boiling brass solution, through which a stiff current should be passing. It remains in this until covered with a coating of brass; it is then to be scratch brushed, given a brushing with pumice and cyanide, and immersed in the ordinary brassing solution, to remain there for an hour or so, with occasional scratch brushing. From this onwards the treatment is the same as that for zinc.

SILVER-PLATING CAST IRON.

Cast iron, etc., is allowed to soak in the pickle for iron until all the scale is loosened, then rinsed from this, and given a good scratch brushing with a steel or stiff brass-wire brush; after this it is passed through the potash, and scrubbed with pumice and cyanide. A coating is then given in the ordinary brassing solution, which coating, with its subsequent passage to the silver-plating solution, requires the same attention to details as has been given for zinc.

NICKEL-PLATING COPPER AND ITS ALLOYS.

The work for this purpose is brought to a finished state on the polishing lathe, that is, it is limed and mopped. Its preparation for nickel-plating is as follows: It is hung in the hot potash for five or ten minutes, then rinsed and passed through the cyanide dip, and given a good brushing with a paste made of equal parts of Sheffield lime and whiting made into a paste with cyanide. After this it is thoroughly rinsed in cold water, swilled through the hot water to free it from all traces of cyanide, and immediately immersed in the nickeling solution, with a current density such that hydrogen bubbles occasionally rise from the work. An immersion of from one to two hours will give a good wearing coat. If a thicker coating is required, the work must be removed from the bath and given a good scratch brushing with a steel-wire brush, and a subsequent scouring with flour of emery and water before being returned to the bath.

For ordinary work there is a sufficient thickness when the deposit has become dull all over. It is then removed from the bath, swilled in hot water, dried out in sawdust, and brought to a high polish again with lime bobs and mops.

NICKEL-PLATING CASTINGS.

These are given a soaking in the acid pickle until all scale, etc., is loosened, and after having been rinsed and scratch brushed with a stiff wire brush to remove all the loosened sand, etc., they are given a boiling in the potash, followed by a scrubbing with pumice powder and cyanide. After having shaken the excess of water away, they are to be plunged for an instant, with shaking, in the ordinary acid dip for these metals, from which they are rinsed in abundance of water. If they do not emerge from this with uniform brightness, another scrubbing with pumice is to be given and the dip in the acid repeated.

They are then swilled in boiling water for a few seconds, and on removal shaken a bit to remove the water, and then passed through the bright acid dip, from which, after a thorough swilling in cold and hot water, they are immediately immersed in the nickeling solution.

NICKEL-PLATING WROUGHT WORK.

This work, if it is not intended to give it a heavy intermediary deposit of copper, has to be completely polished. The prices ruling for modern bicycle work demand that the nickeling should be thrown in, the charge being really only enough to cover the polishing. The work consists of polishing and colouring the object, after which it is nickeled. It is prepared by being passed through the hot potash, given a gentle brushing with whiting, or at most with the fine pumice. It is then rinsed and immersed in the nickeling solution, in which it is allowed to remain only until the deposit commences to dull the brilliance of the polish; it is then removed, swilled in hot water, and sent into the polishing shop to be given a rub over with the lime bob and coloured with the mop.

Nickel deposits, even when carried to a decent coating, are porous, and if the basis metal is unprotected iron or steel it offers little or no protection to the metal from the atmosphere, with the consequence that oxidisation is started which eats its way between the iron and the nickel, the pair making a good galvanic couple, to the utter destruction of the nickel deposit.

The price of silver having so considerably come down during recent years, it is a question if nickeling will not be entirely superseded by silver as a consequence of this reduction in price. The only remaining claim that nickeling possesses to our consideration is its hardness.

For good nickeling on polished iron or steel surfaces the process is as follows. The work is immersed in the boiling potash for five or ten minutes, and then given a good scrubbing with the pumice powder and immersed in the brassing solution with a fairly stiff current. When covered with a coating of brass, it is removed and given a good scratch brushing; after this, another scrubbing with pumice and cyanide with a return to the brassing solution for an hour, with the usual precautions. At the expiration of this time, when it should have a decent coating of brass, it is again scratch brushed, scoured with pumice, and all traces of cyanide washed away by rinsing in boiling water, and then immersed in the acid copper bath, in which it should remain for a couple of hours, with a current density equivalent to 20 ampères per square foot of surface.

On removal from this it has to be washed, dried, and polished with the lime bobs and mops to a finished state. In this stage it can be considered as copper, and its treatment for nickeling is the same as that just given for that metal.

NICKEL-PLATING ZINC.

Zinc work, after being polished, is immersed in boiling potash for a few minutes, and given a scrubbing with the lime and whiting paste, and then immersed in the brassing solution. When struck, it is removed and given a good scratch brushing, and, after a brushing with the pumice paste, is returned to the bath for an hour, with the attention to details as before given.

Having obtained a fair coating of brass, the work is scratch brushed, and, if desired, coloured up with the mop and crocus. It then goes through the same treatment for nickeling as that given for copper and its alloys.

It is unnecessary to give any more examples, as what has been given clearly illustrates all the precautions necessary to be taken in preparation of work for the bath. It is to be remembered that the

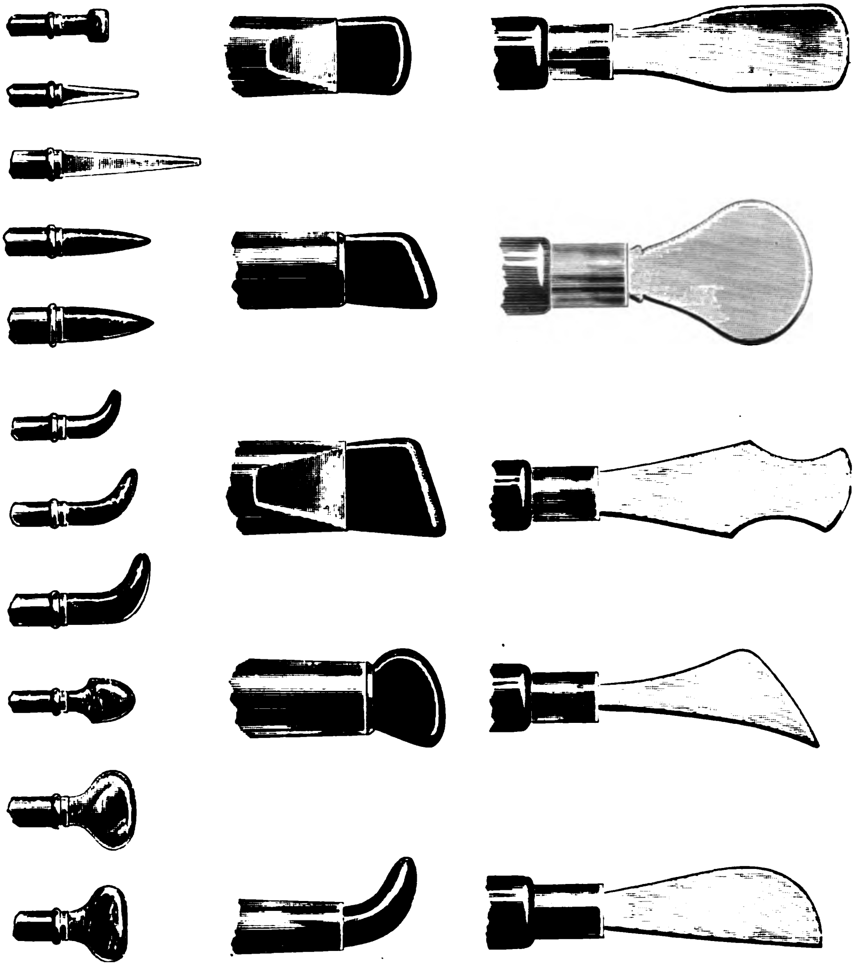


FIG. 80.—VARIOUS FORMS OF BURNISHERS.

metals do not deposit with good adherence on metals similar to themselves; so that if it is required even to deposit copper on copper, it is advisable to give an intermediary coating of brass. The same with silver, etc. etc.

Such metals as zinc, iron and steel, etc., if they are to be thickened in the acid copper bath, must have a sufficient thickness of brassing to protect their base thoroughly from the action of the acid.

To obtain adherent coatings successfully, the metal that is to be coated must be neutral in the intended electrolyte; if not so naturally, it must have a preliminary coating of a metal that is.

As important a point as any is thorough cleanliness, with abundance of rinsing after each operation, and an unsparing use of the pumice and scouring brush.

FINISHING AND COLOURING WORK

Plated work on leaving the bath is swilled in boiling water, scratch brushed, and dried out in hot sawdust.

Plain work can, in skilful hands, be

polished by the leather bobs and lime, coloured with mop and rouge stick, and given a final finish with the flannel dolly charged with rouge powder. Great care is required not to cut through the plating at the edges, etc. Deposits of gold and silver after the scratch brushing are burnished with steel and stone burnishers lubricated with soapy water.

The steel burnishers, having comparatively sharp edges, are used for the first or groundwork process, and bloodstone or agate for the finishing process. Both are to be kept plentifully supplied with soapsuds.

The tools must be kept free from cracks, and well polished by constant rubbing on a piece of leather tacked on a board and charged with putty powder. The illustration in Fig. 80 shows a few of the most usual shapes of burnishers in use.

The tool is held very near the end, and is made to glide backwards and forwards without moving it from the work, and with considerable pressure. For large surfaces the burnisher must be kept directly under the little finger. For removing the marks of the burnisher, or reducing the black polish due to the same, the work can be mopped on the steam spindle with the flannel dolly or felt discs, charged with rouge powder; the polishing dirt, etc., being afterwards removed by rubbing with flannel rag charged with lime or rouge, the dirt held in crevices, etc., being washed out with a soft brush and soap and water.

The wood dust used for drying out must be sifted poplar, maple, or box, or any wood free from tannin or resin.

Silver-plated work which is only used for decoration or light usage, such as epergnes, biscuit boxes, etc., can be given a coating with the brush of, or may be dipped in, a colourless varnish made by dissolving guncotton in methyl-acetate. The work is warmed and painted with, or dipped in, this varnish; no skill is required other than avoiding too great local bulks of the varnish. After varnishing, it is placed over a hot plate in an oven or any well warmed place.

For oxidising silver work a hot solution of barium sulphide containing 20 grains of sulphide to the pint is used.

The scratch brushed work is shaken about in this solution until a uniform blue-black coating is obtained. It is then rinsed in boiling water and lightened up as desired.

For uniform greys a brushing with bristle brushes lightly charged with fine pumice powder will produce the desired result. For contrasts the high lights may be rubbed with the fingers lightly charged with fine pumice. By either or both of these means an oxidisation, more or less artistic, can be obtained, depending entirely upon the taste of the operator.

Oxidised work is usually varnished with the above solution of guncotton.

Nickel-plated ware on removal from the vat is rinsed for a few minutes in boiling water, dried out in the sawdust, and then steam polished with the lime bobs and mop, the final colouring being given with the flannel dolly and dry lime.

For directly nickeled iron work a good boiling in linseed oil very considerably retards possible rusting.

MANAGEMENT AND ESTIMATION OF SOLUTIONS.

The current densities given below for the various solutions are given as the current per super foot of surface immersed, but it is always to be remembered that hard-and-fast rules cannot be stated, as the condition of the solution and method of working control the possible current density. As an instance, a silver solution poor in metal will not make so rapid a deposit of its metal in good condition as one richer in metal; movement, which in most cases of deposition is good, also allows of a higher current density. So in all cases the operator must be guided by the condition of the metal being deposited, and regulate his current accordingly. A silver-plating solution with about 2 oz. of metal per gallon should give a good quality deposit, with a current density from 1·5 to 2·5 ampères per square foot.

That for nickeling from the ammonia sulphate solution is from 3½ to 7 amperes per square foot. The best guide for this work is that small gas bubbles should rise slowly from the work without too great violence, and with a certain amount of regularity.

For brassing solutions the current density is entirely controlled by the deposit. If it is too white, a reduction of the current will deposit more of the copper, and so restore the colour. If regulation of the current does not produce the required result, more of the deficient metal must be added to the solution in the same salt as that forming the bath.

In the copper sulphate bath the current density can vary from 12 to 25 amperes per square foot, depending upon the purpose for which the deposit is required, the smaller density giving a satin finished deposit, while the latter gives a good sound homogeneous deposit suitable for the thickening up of types, etc.

For gilding with gold anodes a current density is employed of such a strength that evolution of hydrogen bubbles from the work is just avoided, this strength depending on the richness in metal of the solution under consideration.

For small work, fresh solution prepared daily is advisable, using a piece of platinum wire for anode, which can be walked over the work.

The conditions of the various solutions can be estimated as follows. The anodes of the silver bath (which should be annealed fine silver sheet) when working should be slightly brownish, and turn white in a little while after the stoppage of the current. If they are white whilst working, a too great content of free cyanide is present, with a consequent possible stripping of the deposit. If, on the other hand, the anodes get very dark, with signs of a white salt accumulating upon them, some more cyanide must be added, as if this is allowed to continue the current will be much reduced, if not stopped.

A solution poor in silver is indicated by a rough deposit with a normal current density.

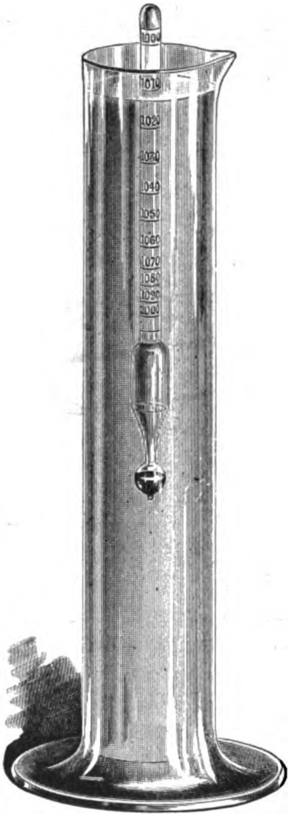


FIG. 81.—THE HYDROMETER.

The hydrometer, Fig. 81, is a simple means of detecting a change of condition of the solution, although not indicating what the change is. If the density of a correct working solution is taken, a change in the level of the hydrometer shows that metal or its solvent has become deficient. If it shows a higher density and no solvent has been added, it indicates a greater content of metal, which must be rectified by adding more of the solvent and diluting. By this instrument and the state of the anodes the condition of this solution is easily arrived at. A comparative table of hydrometer scales is given on p. 133.

SUSPENSION OF ANODES.

There is the necessity of obtaining a good contact between anode and suspending strip or wire, secure against creeping salts and salts caused by the action of the evaporation of the electrolyte.

There are two practical methods of doing this. The best is to immerse totally the anodes in the solution, suspended with a metal that is not attacked by the solution.

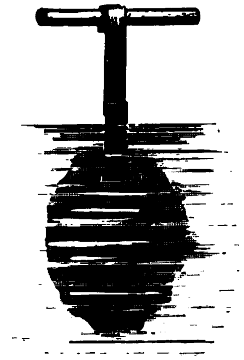


FIG. 82.—SILVER ANODE WITH PLATINUM JOINTING TO COPPER STRIP.

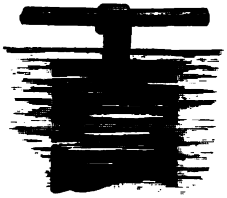


FIG. 83.—NICKEL ANODE SUSPENDED BY NICKEL STRIP.

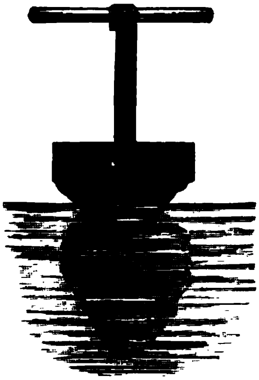


FIG. 84.—ANODE SUSPENDED BY METAL WHICH WOULD BE ATTACKED BY THE SOLUTION.

For silver anodes a short strip of platinum soldered above the level of the solution to a strip of copper, though expensive, will serve for ever, and always ensure good contact. The anode is used up with the least waste, and the cutting through where it leaves the solution, which happens when the connection is made outside the solution, is avoided.

Nickel anodes should have nickel strips riveted to them, and strongly varnished round their junction with the anode.

They are covered with a piece of rubber tubing where they leave the solution. Three modes of suspending anodes are shown in Figs. 82-84.

As a rule, the anode surface should equal the surface to be coated, and in some solutions it is preferable it should exceed this, for the reason that the electrolyte used does not readily dissolve the anode. To some degree this prevents the bath becoming impoverished. An excess of anode surface is used in the nickel, cobalt, and tin solutions.

The distance between anodes and cathodes is regulated to some extent by the shape of the goods being coated. As a rule, for fairly flat objects the distance should never be less than 4 inches. The greater the distance, within limits, separating anodes from cathodes the more homogeneous is the metal deposited, and the more equal is the thickness of the metal spread over the entire surface of the work being coated.

It is advantageous, for the purpose of obtaining an equal thickness of deposit on every part of an object, that anodes should face it on all sides.

For objects with great projections it is a necessity that the anodes should be very distant from them if anything approaching uniformity of deposit is required.

For very deep hollows, a wire of the same metal as the anode (with its end covered with a piece of felt to secure against contact) is led into them, and connected to the anode rod.

CHAPTER IV.—EQUIPMENT AND MANAGEMENT OF PLATING SHOP.

CURRENT GENERATORS—RESISTANCES—AMMETERS—ARRANGEMENT OF CIRCUITS, ETC. —REFERENCE TABLES.

CURRENT GENERATORS.

THE first consideration is the source of current. As dynamos, primary and secondary batteries, have been treated in other parts of this work, it will not be necessary to say more here than that good modern shunt-wound machines for depositing purposes are supplied by any of the well-known makers at about £25 per unit. Although 4 to 5 volts is the most actually required for any of the depositing processes here given, it is recommended for a general shop that a machine giving 10 to 15 volts on full load be installed, thus enabling three or four storage batteries or accumulators to be kept charged for use when the driving engine of the dynamo is stopped; and in the case of typing enabling all-night working.

The size of machine will entirely depend on the volume of the combined baths in the shop when they are fully charged. As a guide, an acid copper bath holding about 130 gallons can easily take 300 amperes. A plating tank of the same capacity can take about 50 amperes.

Accumulators or storage batteries are batteries which store current by virtue of raising the salt of a metal to a higher chemical value (electro-chemically), which salt, under favourable conditions, gives a current on falling to its lower chemical state.

The only practical storage cell at present is lead and its salts, the two elements of which consist of a lead frame or holder as a conductor to the active material, which is respectively spongy lead and lead oxide, with an electrolyte of dilute sulphuric acid. In charging this battery (that is, passing a current from an outside source through it) the current is made to enter the red oxide plate and leave the cell by the spongy lead plate. During the passage of the current the red oxide plate is converted to a higher oxide on the surface, which penetrates deeper and deeper, depending on the length of charge.

The lead oxide plate has by use been designated the positive plate, and for charging is connected to the positive terminal of the dynamo, and for discharging through the baths is connected to the anodes.

The capacity of a cell is dependent upon the amount of this lead oxide that is capable of being converted by means of an outside current into a higher oxide. It will give out about 90 per cent. of the ampere hours required to produce it.

Each cell requires at least 2½ volts to charge—that is, to drive a current through it—and on discharge it can be considered practically as delivering a current at 2 volts; so that for a plating shop not less than three storage cells should be provided, their size or capacity depending upon the normal working current of the shop. It can be considered that every red or positive plate of 1 foot square can discharge at the rate of about 6 amperes, so that a cell with three positive and four negative plates of about 1 foot square each can discharge at the rate of about 20 ampères without injury to the cell. For short periods this can be greatly exceeded.

For shops that are on the line of route of the street mains of some electrical company a motor, driven by current supplied from the mains, can be employed to drive the polishing spindles and dynamo, which, with accumulators in circuit, need only be running as occasion demands, so that no more power need be paid for than is actually used.

For shops working with primary batteries, the Bunsen element is recommended for plating purposes; and for typing what is called the single-cell process is advisable, this being simply a large Daniell cell, with the work as negative element.

A Bunsen element, made up with two thin carbon plates in rectangular porous pots with a flat zinc plate between, is the simplest form to keep in order. The zinc simply being a piece of sheet, cut to size, it can be reversed to equalise the wear, and is easily re-amalgamated. It is about 9″ long by 6″ wide, and is supported in the cell by clamping between two strips of ebonite or waxed hard wood about 1″ × 8″ by ¼″ thick, which rests upon the lead connecting the two carbons. The brass clamp which binds them together also carries the terminal, and contact is made by the second screw which passes through a hole in one of the strips. The two carbon plates are cast into a lead ring, which is enlarged at the ends to fit loose-tight in the porous pot to keep them in position, and then shouldered up to rest on the containing vessel, which may be ebonite, glass, or earthenware. The lead ring carries its terminal at one corner; it is screwed and soldered to the ring.

The carbon plates have a number of holes drilled, about a quarter of an inch from their top edge, to enable the lead on shrinking to grip the plate firmly, the lead ring covering some quarter of an inch down; the plate should be strongly varnished.

For casting the lead a metal former should be made, the carbons supported in position in it, and molten lead at a high temperature poured in to fill the mould. The shoulders at the ends can be sawn out after casting.

The cell is charged with nitric acid in the porous pots, and 12 per cent. sulphuric acid in the outer containing pot.

It gives 2 volts, and 2 or more are to be connected in parallel, so that the surface of zinc equals the area of work in the bath.

For electrotyping the single-cell process is the most economical and least trouble; porous pots, rectangular or round, are suspended or stood in between the work. They are charged with a 12 per cent. dilute sulphuric acid solution, in which the amalgamated zincs are hung from a rod which is in good connection with the rods carrying the work, thus practically short-circuiting a large Daniell cell, in which, like a Daniell cell, its copper sulphate must be kept supplied with copper by always having copper sulphate crystals suspended in it, contained in perforated ebonite or earthenware pockets suspended round the inside of the vat.

The zincs are amalgamated by being soaked in dilute hydrochloric acid and then brushed over with mercury contained in an earthenware tray, the tray also being filled with dilute acid, the excess mercury being allowed to drain well off before immersing in the battery. The zincs must present an uniformly bright appearance; any dull spots must be scoured out, old scouring brushes serving very well for this amalgamating job.

RESISTANCES AND MEASURING INSTRUMENTS.

Each vat should be supplied with its own resistance or current controller and current indicator. The dynamo should also have a resistance in its shunt or field-magnet circuit.

A good resistance for the shunt of the dynamos is made of German silver or platinoid strip, wound in a spiral, and of a gauge dependent on the size of dynamo, etc. The advantage of this form of resistance is that the dynamo can be regulated to a nicety and without breakage of the current, which for this purpose is very important. It is clearly shown in Fig. 85. The movement of the handle makes a contact piece travel over the metal strip spiral, putting more or less of it in circuit. When the contact piece is hard up against the pin in the centre, all the resistance is cut out.

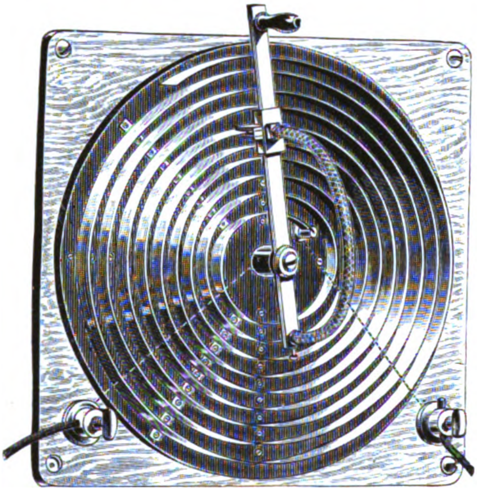


FIG. 85.—SHUNT REGULATING RESISTANCE FOR PLATING DYNAMO.

A useful resistance for the vats is shown in Fig. 86, made of carbon rods in conjunction with a carbon "squeeze-up" shown on the left of the drawing. Here again the size of rods and joining up will depend on the current it will have to carry.

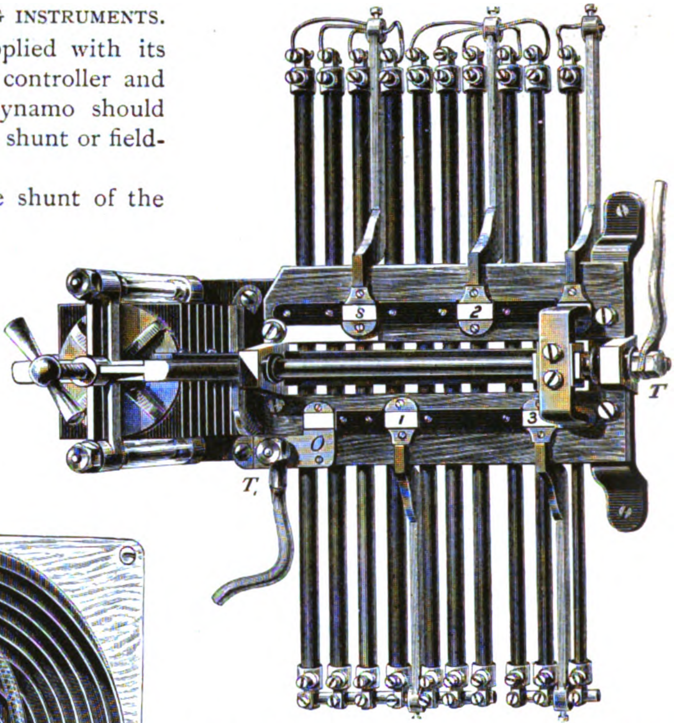


FIG. 86.—RESISTANCE FOR VATS MADE OF CARBON RODS IN CONJUNCTION WITH A CARBON "SQUEEZE-UP."

The one in the drawing has rods 18″ long by about $\frac{1}{2}''$ diameter, which can easily carry from 15 to 20 amperes apiece. As shown in the drawing, the first stud, marked 1, puts in four of these rods in parallel, and at this point it is therefore capable of taking 60 to 80 amperes. By pushing the contact brush on to the next stud to the right, marked 2, three rods in parallel are put in series with the first four; stud 3 puts two rods in parallel in series with the three and four, and the last stud puts one in series with the two, three, and four rods.

Thus the last stud throws in circuit four times the resistance of the first, three times

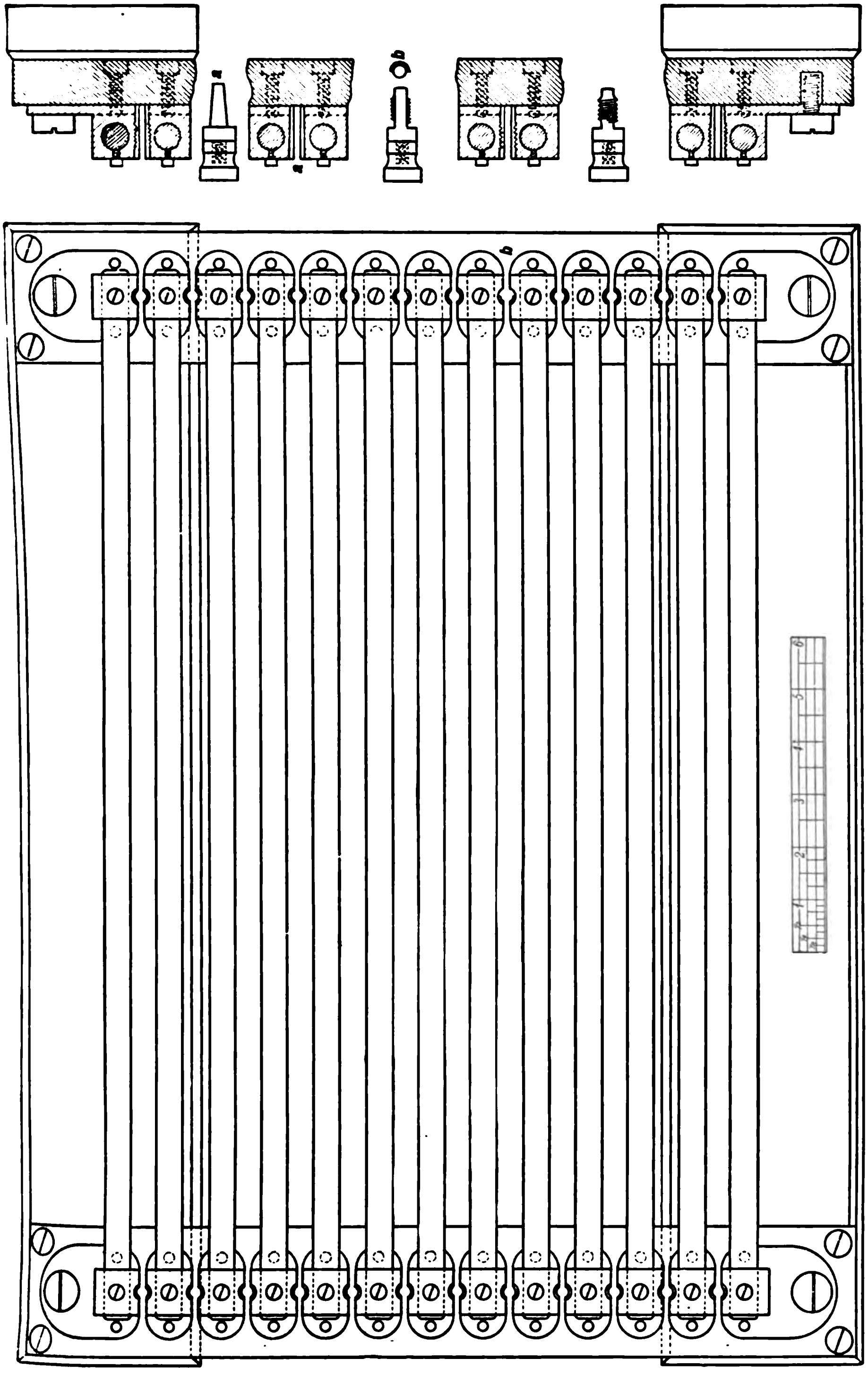


FIG. 87.—CARBON ROD RESISTANCE TO CARRY 20 AMPERES.

that of the second, and twice that of the third, while with each stud there is the possibility of fine regulation by turning the handle on the left either to tighten the carbon plates for a reduction of resistance or to loosen them for increase.

When the sliding contact is on the stud marked S, only the carbon squeeze is in circuit, as that stud is in metallic contact with the iron frame enclosing the carbon plates.

One terminal of the resistance is at the end of the brass rod on which the sliding contact moves, and marked T; the other is on the stud marked O, and is connected to the carbon plate contact plate. It is thus seen that if the slider is brought on to this stud marked O the resistance is very thoroughly short-circuited.

The contact plates are the flattened ends of the brass uprights which support the carbon rods and carry the current to them. At the bottom end the carbons are rigidly held in brass cups screwed to the brass rod that is fixed in the end of the upright. The other or top ends have flexible connections so as to enable the rods to expand freely.

The rods are kept in place by passing through iron screw-eyes at the back of the board, so that no damage can be done if such a current is sent through them that they are made to glow.

Another useful form of the carbon rod resistance is shown in Fig. 87, which consists of two slate strips screwed to wood battens top and bottom. On the slate strips are bolted a number of brass blocks, having a hole through them large enough for the carbon rod to pass freely, and a small screw on top to clamp the rod in position and to make contact.

Between each pair of blocks (which are about $\frac{1}{8}''$ apart) is a taper or screw hole, adjoining blocks carrying half each, as is clearly shown in the section, so that when a screw or plug is inserted two blocks are made as one. The drawing shows two kinds of connectors, screw and taper. The screw plugs are more reliable, and do not strain the brass block as do the taper plugs.

By this arrangement any possible combination of the rods can be made, all in series or all in parallel, or one, two, three, four in parallel or series, etc. etc.

The terminals for an even number of rods will be top and bottom of either side, and for an odd number left hand top and right-hand bottom, or *vice versâ*.

The drawing shows a frame with a dozen rods, but one with six rods of sufficient size to carry the current, in conjunction with a carbon squeeze, will be quite sufficient in ordinary practice. The rods can be made to carry from 15 to 20 amperes if of $\frac{1}{2}''$

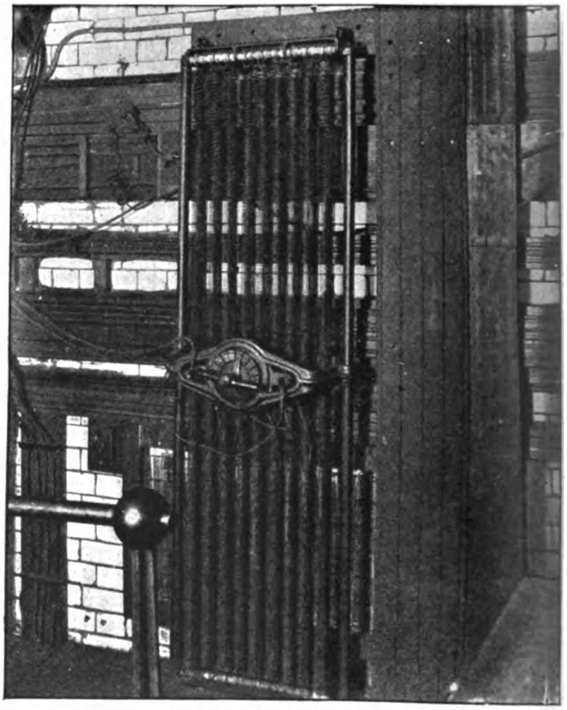


FIG. 88.—WIRE RESISTANCE.

diameter, and must be mounted on a fireproof frame, as at the latter current density they glow.

In Fig. 88 is shown an ordinary wire resistance provided with a regulating switch by which the number of spirals in the circuit may be varied one at a time. The frame shown has a resistance of about 1 ohm per spiral, and is capable of carrying 100 amperes continuously.

A cheap and simple form of ampere meter for measuring the current supplied to the baths is illustrated in Fig. 89. It is a gravity controlled instrument, and is not very liable to disturbance from external magnetic fields. A permanent magnet instrument is illustrated in Fig. 90. This type has an advantage over the above instrument in that it is not only quite independent of external fields, but serves further to indicate the direction of current; it is provided with a central zero, and the current flows through the instrument in the same direction as the direction of motion of the pointer from zero. These instruments are of great service, as they enable the operator to tell at a glance whether the current has by any chance reversed, and in an accumulator circuit they indicate with perfect clearness whether the cells are being charged or discharged.

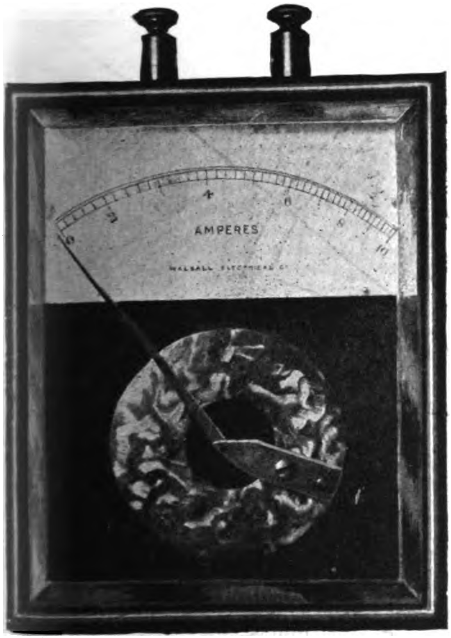


FIG. 89.—GRAVITY CONTROLLED AMMETER.

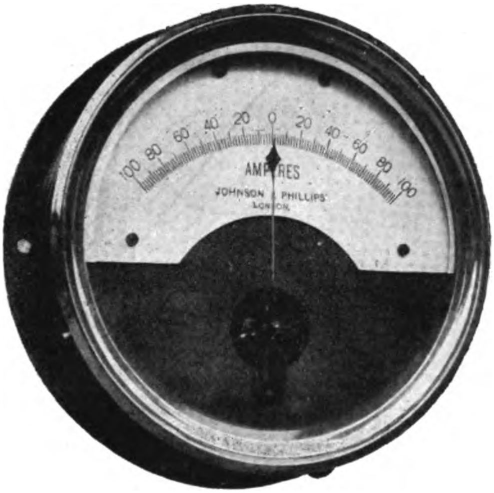


FIG. 90.—PERMANENT MAGNET AMMETER.

Fig. 91 gives a scale drawing of a ring contact switch, of cheap and substantial construction, suited for fairly large currents at a low voltage, such as obtain in plating shops. The switch shown is suitable for currents up to about 120 amperes. The drawing is self explanatory. The ring contacts are sprung so as to grip the fixed contacts well, the amount of spring being usually regulated by a screw (not shown in the drawing) which passes freely through the upper half ring and engages with the lower half. By this means the grip can be increased to any desired extent. This type of switch is capable of very hard and rough wear. The left-hand terminal may be connected to the positive pole of the dynamo, and the top one to the positive of the accumulators. The other two are then connected to the anodes of the baths. The switch thus enables either the dynamo or

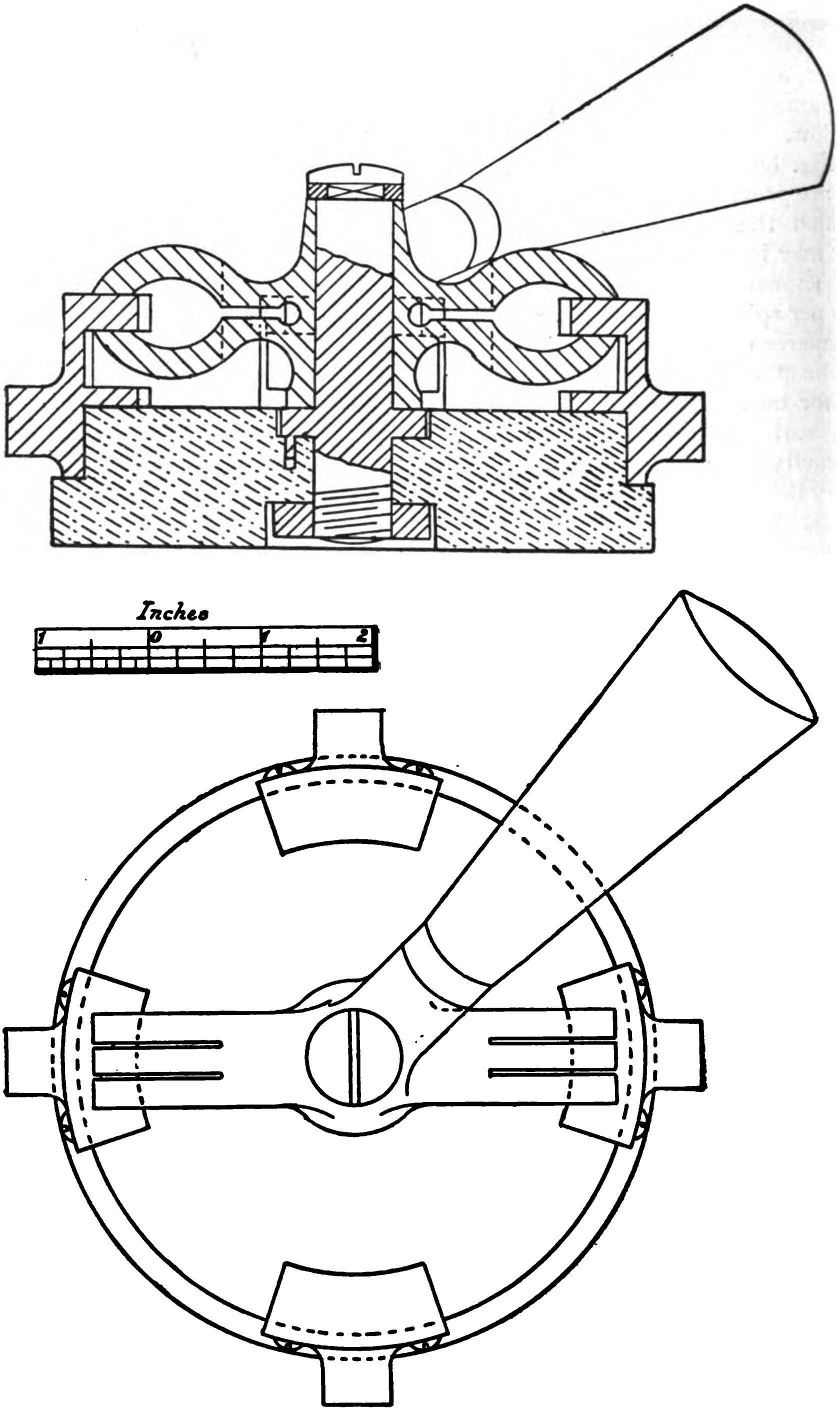


FIG. 91.—RING CONTACT SWITCH.

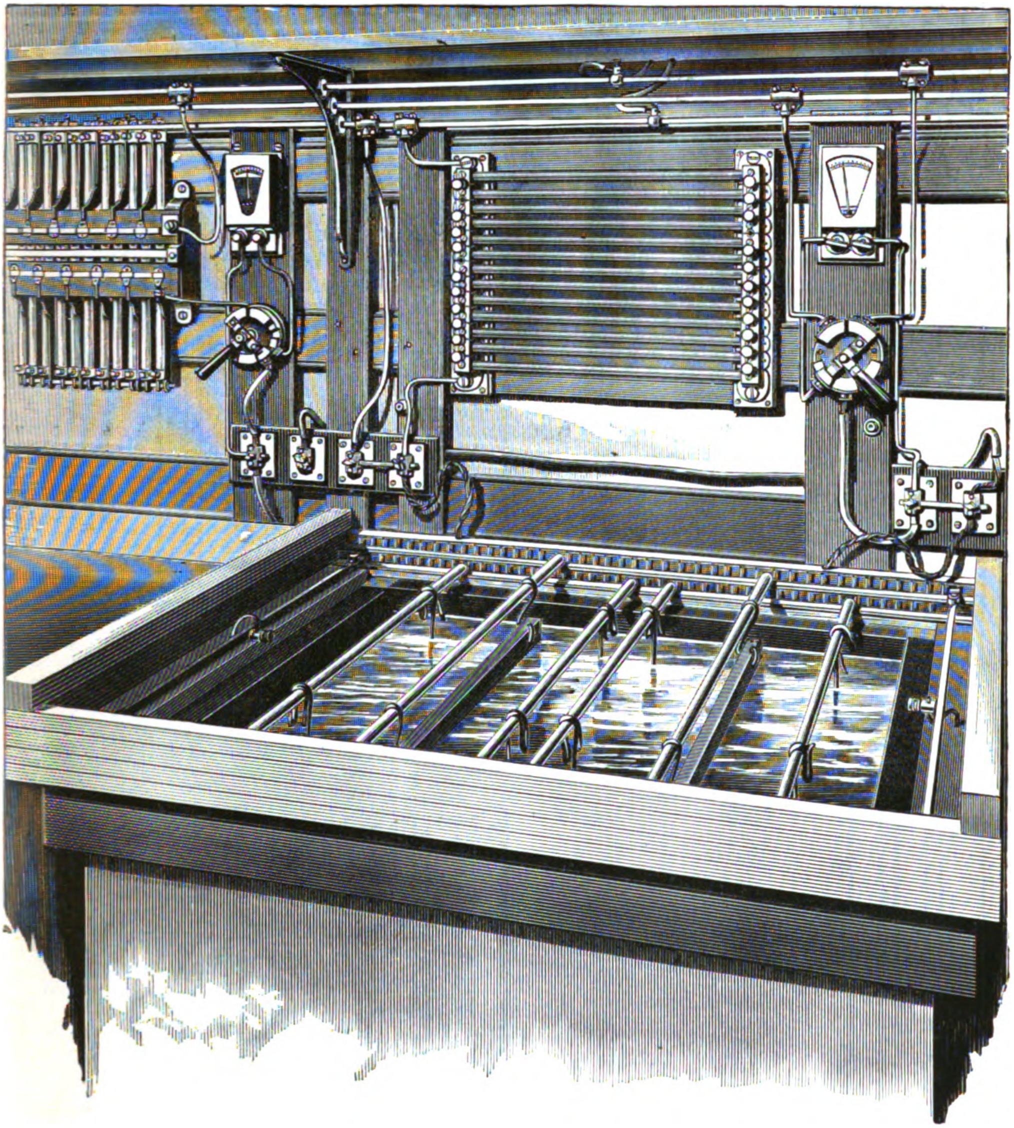


FIG. 92.—PLATING BATH, COMPLETE WITH TOP FRAME, CARBON RESISTANCES, SWITCHES, AMMETERS, ETC.

accumulators to be used independently. In the position shown the dynamo would be serving the vats. Other contacts may be fixed in the blank spaces, enabling other connections to be effected through the switch if desired. For example, two small contacts, not quite filling the space, may be placed between the top and the left-hand contacts, and form extensions to them. By moving the switch handle through 45° in a downward direction the left-hand ring could be brought into con-

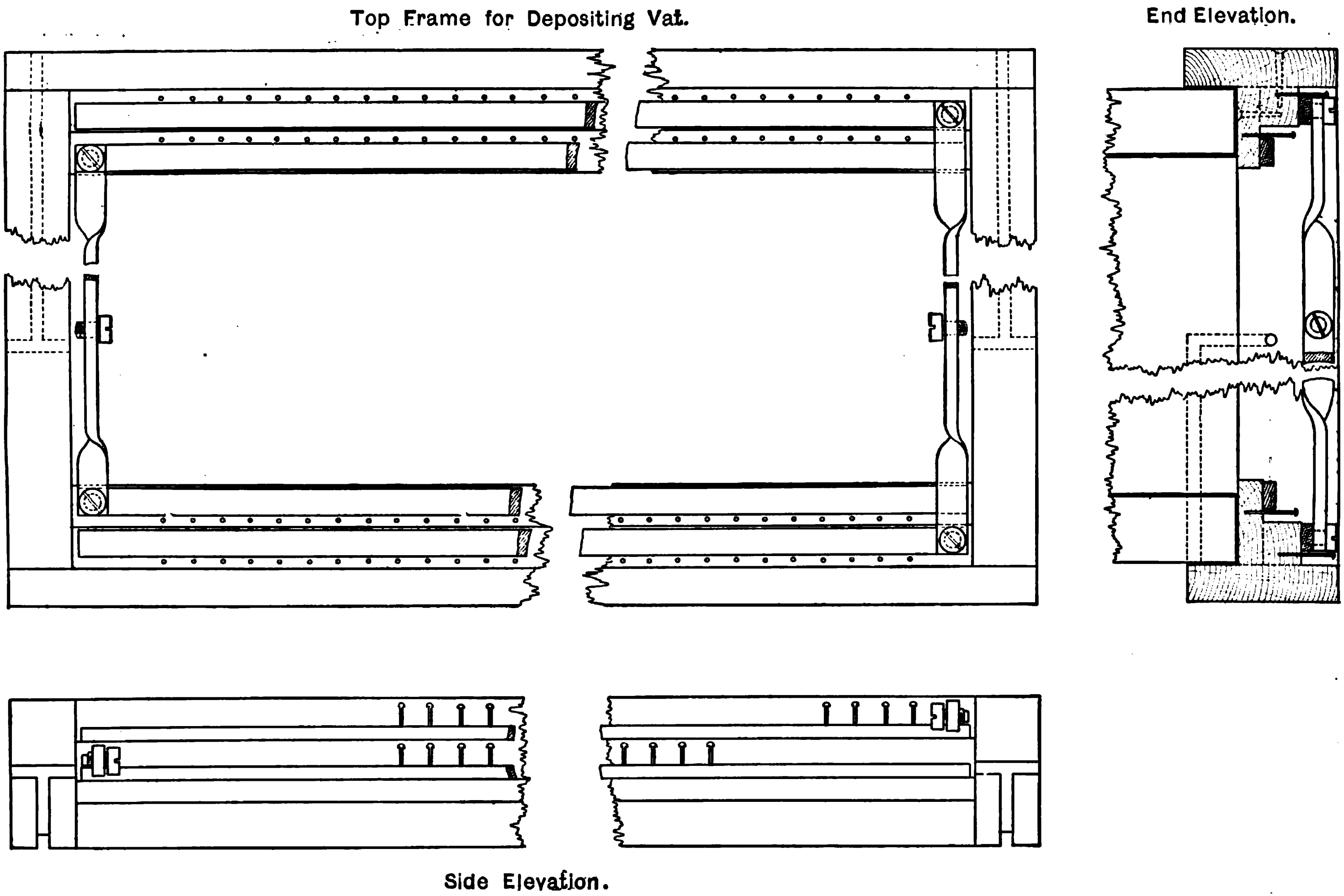


FIG. 93.—TOP FRAME FOR SUPPORTING AND MAKING CONTACT WITH ANODE AND CATHODE RODS OF DEPOSITING BATHS. SCALE ABOUT 1 : 3.

tact with both the said extensions simultaneously, and a similar provision being made between the right-hand and bottom terminal, the dynamo and accumulators could be made to serve the baths in parallel.

An illustration is given, in Fig. 92, showing a bath complete with its resistance, ammeter, switch and leads, etc.; also a detailed drawing, in Fig. 93, of a useful frame for the top of the vats to carry the work and anodes. The work always being put on the lower ledge, all danger of suspending work on anode rods is obviated. The metal work is also readily removed to be cleaned. The drawing is to scale, and suitable for any size up to 200 amperes.

The main or dynamo switch-board must have a switch with four contacts, and should be connected up so as to enable the following circuits to be made: First, dynamo to baths; second, dynamo to accumulators; third, dynamo to the baths and accumulators in parallel; and fourth, dynamo accumulators and vats in series.

In the accumulator circuit there must be a magnetic cut out, an ammeter, and a controlling switch to enable the accumulators to be connected in series or parallel.

Comparison of Hydrometer Scales.

Specific Gravity, Degrees.	Degrees, Baumé.	Specific Gravity, Degrees.	Degrees, Baumé.	Twaddell, Degrees.	Specific Gravity, Degrees.	Degrees, Baumé.	Twaddell, Degrees.
·817	40	1·000	0 or 10	0	1·337	37	
·827	38	1·007	1		1·349	38	70
·837	36	1·014	2		1·361	39	
·847	34	1·020	3		1·375	40	
·856	32	1·028	4		1·388	41	
·871	30	1·036	5		1·401	42	80
·880	28	1·041	6		1·414	43	
·892	26	1·049	7	10	1·428	44	
·903	24	1·057	8		1·442	45	90
·915	22	1·064	9		1·456	46	
·928	20	1·072	10		1·470	47	
·942	18	1·080	11		1·485	48	
·955	16	1·088	12		1·500	49	100
·970	14	1·096	13	20	1·515	50	
·985	12	1·104	14		1·531	51	
1·000	0 or 10	1·113	15		1·546	52	110
		1·121	16		1·562	53	
		1·130	17		1·579	54	
		1·138	18		1·596	55	120
		1·147	19	30	1·615	56	
		1·157	20		1·634	57	
		1·166	21		1·653	58	130
		1·176	22		1·671	59	
		1·185	23		1·690	60	
		1·195	24	40	1·709	61	140
		1·205	25		1·729	62	
		1·215	26		1·750	63	150
		1·225	27		1·771	64	
		1·235	28		1·793	65	
		1·245	29	50	1·815	66	160
		1·256	30		1·839	67	170
		1·267	31		1·864	68	
		1·278	32		1·885	69	
		1·289	33		1·909	70	180
		1·300	34	60	1·935	71	
		1·312	35		1·960	72	190
		1·324	36				

LIST OF

NAME.	SYMBOL.	COMBINING OR ATOMIC WEIGHT.	VALENCY, THE FIRST FIGURE BEING THE MOST USUAL COMPOUND.	CHEMICAL EQUIVALENTS.	ELECTRO-CHEMICAL EQUIVALENTS IN GRAMMES PER COULOMB. 1-10TH OF THE C.G.S. UNITS.	WEIGHT DEPOSITED IN ONE HOUR BY ONE AMPÈRE. 480 GRAINS = 1 OZ. TROY. 437·5 GRAINS = 1 OZ. AVOIRDUPOIS. 15·4324 GRAINS = 1 GRAMME.		A THICKNESS PER SQUARE INCH OF SURFACE. 25·4 MILLIMETRES = 1 INCH. 1·0 MILLIMETRES = ·03937 INCH. 1 SQUARE INCH = 645·15 SQUARE MILLIMETRES. 1 SQUARE DECIMETRE = 15·5 SQUARE INCHES.		APPROXIMATE STANDARD WIRE GAUGE.	SPECIFIC GRAVITY OR RATIO HEAVINESS OF A GIVEN SUBSTANCE TO THE HEAVINESS OF PURE WATER AT 62° F., 16·7° C.
						Grammes.	Grains.	Inches.	Millimetres.		
Aluminium	Al.	27·5	3	9	0·00009317	0·3354	5·175	·007875	·20	36	2·67
Antimony (Stibium)	Sb.	122	3 and 5	40·6	·00042025	1·5130	23·350	·013584	·345	29	6·72
Arsenic	As.	75	3 and 5	25·0	·00025880	0·9317	14·378	·009806	·249	33	5·63
Barium	Ba.	137	2	68·5							4·00
Bismuth	Bi.	210	3 and 5	70	·00072464	2·6087	40·258	·016251	·413	27	9·799
Boron	B.	10·9	3	3·6							2·68
Bromine	Br.	80	1	80·0							2·97
Cadmium	Cd	112	2	56·0	·00057971	2·0870	32·207	·014811	·376	28	8·67
Cæsium	Cs.	133	1	133·0							
Calcium	Ca.	40	2	20·0							3·10 to 1·578
Carbon	C.	12	4	3·0							3·50
Cerium	Ce.	138	2 — 4	46·0							
Chlorine	Cl.	35·5	1	35·5							2·45 gaseous
Chromium	Cr.	52·5	3 — 6	17·5	·00018116	0·6522	10·052	·005687	·144	38 — 39	6·81
Cobalt	Co.	59	2	29·5	·00030538	1·0994	16·966	·007715	·195	36	8·50 to 8·7
Copper (Cuprum)	Cu.	63·5	2 and 1	31·75	·00032867	1·1832	18·260	·008104	·205	35	8·88 to 8·95
Didymium	D.	142·5	2 — 3	—							
Erbium	E.	112·6	3 — 2	56·3							
Fluorine	F.	19	1	19·0							1·32
Gallium	Ga.	69·86	3	23·0							5·9
Glucinum	G.	9·3	2 — 3	4·7							2·1
Gold (Aurum)	Au.	196·6	3	65·5	·00067806	2·4410	37·670	·007721	·196	36	19·50
Hydrogen	H.	1	1	1	000010352*	·00062112	·00958537				0·069 gaseous
Indium	In.	113·4	3	37·8							7·4
Iodine	I.	127	1	127·0							4·98
Iridium	Ir.	197	4	49·2	·00050932	1·8335	28·296	·005291	·134	39	21·15
Iron (Ferrum)	Fe.	56	2	28·0	·00028986	1·0435	16·103	·007826	·198	35 — 36	7·70
Lanthanum	La.	92	2 — 3	46·0							
Lead (Plumbum)	Pb.	207	2 — 4	103·5	·00107140	3·8571	59·525	·021131	·536	24 — 25	11·35
Lithium	L.	7	1	7·0							0·593
Magnesium	Mg.	24·3	2	12·1	·00012526	0·4509	6·959	·016190	·411	27	1·74
Manganese	Mn.	55	2 — 6	27·5	·00028468	1·0248	15·816	·007821	·198	36	8·00
Mercury (Hydrargyrum)	Hg.	200	2 and 1	100·0							13·596 at 0° C.
Molybdenum	Mo.	96	6	16·0							8·60
Nickel	Ni.	59	4	29·5	·00030538	1·0994	16·966	·007894	·190	36	8·82
Niobium	Nb.	94	5	19·5							6·67
Nitrogen	N.	14	3 and 5	4·6							0·972 gaseous
Osmium	Os.	199·4	6	33·3							21·3
Oxygen	O.	16	2	8·0	·00542448						gaseous 1·088
Palladium	Pd.	106·5	2 and 4	26·6	·00027536	0·9913	15·298	·005291	·134	39	11·8
Phosphorus	P.	31	3 and 5	10·3							1·84
Platinum	Pt.	197	4 and 2	49·2	·00050931	1·8341		·004843	·123	40	21·53
Potassium (Kalium)	K.	39·1	1	39·1							1·865
Rhodium	Ro.	104·3	3	34·8							12·10
Rubidium	Rb.	85·4	1	85·0							1·50
Ruthenium	Ru.	104·2	4	26·0							11·40
Selenium	Se.	79·5	2	39·7							4·28
Silicon (Silicium)	Si.	28	4	7·0							2·49
Silver (Argentum)	Ag.	108	1	108	·0011180	4·0249	62·113	·023142	·588	24	10·50
Sodium (Natrium)	Na.	23	1	23							0·972
Strontium	Sr.	87·5	2	43·7							2·54
Sulphur	S.	32	2	16·0							2·045
Tantalum	Ta.	182	5	36·4							10·78
Tellurium	Te.	129	2	64·5							6·18
Thallium	Tl.	204	1	204·0							11·86
Thorinum	Th.	231·5	—	119·0							7·70
Tin (Stannum)	Sn.	118	2 and 4	59·0	·00061077	2·1988	33·932	·018414	·467	26	7·29
Titanium	Ti.	50	4	12·5							5·30
Tungsten (Wolfram)	W.	184	6	30·7							19·10
Uranium	U.	120	4 — 6	60·0							18·40
Vanadium	V.	51·3	3 — 5	17·1							5·50
Yttrium	Y.	61·6	3 — 2	30·0							
Zinc	Zn.	65	2	32·5	·00033644	1·2112	18·691	·010415	·264	32	6·86 7·15
Zirconium	Zr.	89·5	4	22·4							4·20

* Lord Rayleigh's determination; 1 gramme of hydrogen at 0° C. and 760 m.m. pressure occupies a space of 11 16345 litres.

ELEMENTS.

Fusing Point in ° F. and ° C.	Weight per Cubic Inch.
	lbs.
1300° F. 705° C.	·096
800° F. 1150 426·7° C. 621	·242
515° F. 268° C	
507° F. 264° C.	·353
7° C.	
608° F. 442° F. 320° C. 228° C.	
1150° C.	
1996° F. 1091° C.	·32
2015° F. to 3812° F — 1101° to 2100° C.	·665
176° C.	
107° C.	
2912° F. to 3092° F. — 1594° to 1922° C.	·28
633° to 599·4° F. — 333° to 315° C.	·412
180° C. 235° C. 356° F.	
	·289
Boiling point 350°; Solid state 39° C.;	·49117
2912° F. 1594° C.	·321
1360° to 1380° C.	
1480° to 44° C., 2600° C.	·775
62·5° C. 144·5° F.	
38·5° C. 101·3° F.	
217° C.	
1873° F. 1023° C.	·379
97·6° C. 207·7° F.	
238° F. 114° C.	
115° C.	
380° C.	
561° F. 294° C.	
442° to 458·4° F. — 228° to 237° C.; Cubic inch ·262 lbs.	
773° F. 412° C.	·252

Grouping of the Elements.	
Non-metals.	Hydrogen
	Chlorine
	Oxygen
	Nitrogen
	Carbon
	Bromine
	Iodine
	Fluorine
	Sulphur
	Selenium
	Tellurium
	Phosphorus
	Silicon
Group 1. Metals of the Alkalies.	Boron
	Potassium
	Sodium
	Lithium
	Cæsium
Group 2. Metals of the Alkaline Earths.	Rubidium
	Barium
	Strontium
	Calcium
Group 3. Metals of the Earth.	Aluminium
	Gallium
	Glucinum
	Yttrium
	Erbium
	Cerium
	Lanthanum
Group 4. Magnesian metals.	Didymium
	Magnesium
	Zinc
	Cadmium
Group 5. Metals Allied to Iron.	Cobalt
	Nickel
	Uranium
	Iron
	Chromium
	Manganese
Group 6. Metals Allied to Tin.	Tin
	Titanium
	Zirconium
	Thorinum
	Molybdenum
	Tungsten
	Niobium
	Tantalum
	Vanadium
	Arsenic
	Antimony
	Bismuth
Group 8. Noble Metals.	Copper
	Lead
	Thallium
	Indium
	Mercury
	Silver
	Gold
	Platinum
	Palladium
	Rhodium
	Ruthenium
	Osmium
	Iridium

Relative Electric Conductivity of Some Metals.	
Silver	100
Copper	100
Gold	81
Aluminium	55·1
Sodium	37·4
Zinc	30·2
Magnesium	25·4
Cadmium	23·7
Calcium	22·14
Potassium	20·8
Platinum	
Lithium	19
Cobalt	17·22
Iron	16·8
Platinum	16·7
Palladium	16·4
Tin	15·2
Nickel	13·11
Thallium	9·2
Lead	8·8
Strontium	6·71
Arsenic	4·8
Antimony	4·6
Mercury	2·5
Bismuth	1·245
Graphite	0·07

Arrangement of the Common Metals in Electro-Chemical Series.	Heat Units Evolved in Combination with		
•		1 Atom of Oxygen O.	2 Atoms of Chlorine Cl_2.
Potassium	K_2.	97,200	211,220
Sodium	Na_2.	100,200	195,380
Magnesium			
Manganese	Mn.	* 94,770	111,990
Zinc	Zn.	86,400	97,210
Iron	Fe.	* 68,280	82,050
Cadmium	Cd.	* 65,680	93,240
Cobalt	Co.	* 63,400	76,480
Nickel	Ni.	* 60,840	74,530
Lead	Pb.	50,300	82,770
Tin	Sn.	* 68,090	80,790
Bismuth			
Copper	Cn.	37,160	51,630
Mercury	Hg.	30,660	63,160
Silver	Ag_2.	5,900	58,760
Platinum			
Gold			
Hydrogen	H_2.	68,360	†44,000
Antimony			
The Non-Metals			

The above grouping is in the relative degrees of affinity for oxygen, Group 1 having the highest.

* These oxides are hydrated, the remaining are anhydrous.

† This number refers to the gaseous hydrogen chloride.

SPECIFIC GRAVITIES OF SULPHURIC, NITRIC, AND HYDROCHLORIC ACIDS.

%.	H_2SO_4.	HNO_3.
100	1·8426	1·500
9	1·8420	1·498
8	1·8406	1·496
7	1·8400	1·494
6	1·8384	1·491
5	1·8376	1·488
4	1·8356	1·485
3	1·8340	1·482
2	1·8310	1·479
1	1·8270	1·476
90	1·8220	1·473
9	1·8160	1·470
8	1·8090	1·467
7	1·802	1·464
6	1·794	1·460
5	1·786	1·457
4	1·777	1·453
3	1·767	1·450
2	1·756	1·446
1	1·745	1·4424
80	1·734	1·4385
9	1·722	1·4346
8	1·710	1·4306
7	1·698	1·4269
6	1·686	1·4228
5	1·675	1·4189
4	1·663	1·4147
3	1·651	1·4107
2	1·639	1·4065
1	1·627	1·4023
70	1·615	1·3978
9	1·604	1·3945
8	1·592	1·3882
7	1·580	1·3833
6	1·568	1·3783
5	1·557	1·3732
4	1·545	1·3681
3	1·534	1·3630
2	1·523	1·3579
1	1·512	1·3529
60	1·501	1·3477
9	1·490	1·3427
8	1·480	1·3376
7	1·469	1·3323
6	1·4586	1·3270
5	1·448	1·3216
4	1·438	1·3163
3	1·428	1·3110
2	1·418	1·3056
1	1·408	1·3001
50	1·398	1·2947
9	1·3886	1·2887
8	1·379	1·2826
7	1·370	1·2765
6	1·361	1·2705
5	1·351	1·2644
4	1·342	1·2583
3	1·333	1·2523
2	1·324	1·2464
1	1·315	1·2402
40	1·306	1·2341

%.	H_2SO_4.	HNO_3.	HCl.
40	1·306	2341	·1966
9	1·297	2277	·1922
8	1·289	2212	·1878
7	1·281	2148	·1840
6	1·272	2084	·1786
5	1·264	2019	·1738
4	1·256	1958	·1689
3	1·247	1895	·1640
2	1·239	1833	·1584
1	1·231	1770	·1536
30	1·223	1709	·1484
9	1·215	1648	·1433
8	1·2066	1587	·1382
7	1·1980	1515	·1333
6	1·190	1467	·1282
5	1·182	1403	·1232
4	1·174	1345	·1182
3	1·167	1286	·1131
2	1·159	1227	·1081
1	1·1515	1168	·1031
20	1·144	1109	·0981
9	1·136	1051	·0931
8	1·129	0993	·0882
7	1·121	0935	·0832
6	1·1136	0878	·0783
5	1·106	0821	·0734
4	1·098	0764	·0684
3	1·091	0708	·0635
2	1·083	0651	·0586
1	1·0756	0595	·0537
10	1·068	0540	·0487
9	1·061	0485	·0438
8	1·0536	0430	·0309
7	1·0464	0375	·0340
6	1·039	0320	·0292
5	1·032	0267	·0244
4	1·0256	0212	·0196
3	1·019	0159	·0146
2	1·013	0106	·0098
1	1·0064	0053	·0049

Saturation of liquid HCl = 40 per cent. of HCl gas.

Comparison of Thermometer Scales, Centigrade and Fahrenheit.

Cent. Deg.	Fah. Deg.	Cent. Deg.	Fah. Deg.	Cent. Deg.	Fah. Deg.	Cent. Deg.	Fah. Deg.	Cent. Deg.	Fah. Deg.	Cent. Deg.	Fah. Deg.
0	32	18·9	66	37·8	100	56·7	134	75·5	168	94	201·2
0·5	33	19	66·2	38	100·4	57	134·6	76·	168·8	94·4	202
1	33·8	19·4	67	38·3	101	57·2	135	76·1	169	95	203
1·1	34	20	68	38·9	102	57·8	136	76·7	170	95·5	204
1·7	35	20·5	69	39	102·2	58	136·4	77	170·6	96	204·8
2	35·6	21	69·8	39·4	103	58·3	137	77·2	171	96·1	205
2·2	36	21·1	70	40	104	58·9	138	77·8	172	96·7	206
2·8	37	21·7	71	40·5	105	59	138·2	78	172·4	97	206·6
3	37·4	22	71·6	41	105·8	59·4	139	78·3	173	97·2	207
3·3	38	22·2	72	41·1	106	60	140	78·9	174	97·8	208
3·9	39	22·8	73	41·7	107	60·5	141	79	174·2	98	208·4
4	39·2	23	73·4	42	107·6	61	141·8	79·4	175	98·3	209
4·4	40	23·3	74	42·2	108·0	61·1	142	80	176	98·9	210
5	41	23·9	75	42·8	109	61·7	143	80·5	177	99	210·2
5·5	42	24	75·2	43	109·4	62	143·6	81	177·8	99·4	211
6	42·8	24·4	76	43·3	110	62·2	144	81·1	178	100	212
6·1	43	25	77	43·9	111	62·8	145	81·7	179	100·5	213
6·7	44	25·5	78	44	111·2	63	145·4	82	179·6	101	213·8
7	44·6	26	78·8	44·4	112	63·3	146	82·2	180	101·1	214
7·2	45	26·1	79	45	113	63·9	147	82·8	181	101·7	215
7·8	46	26·7	80	45·5	114	64	147·2	83	181·4	102	215·6
8	40·4	27	80·6	46	114·8	64·4	148	83·3	182	102·2	216
8·3	47	27·2	81	46·1	115	65	149	83·9	183	102·8	217
8·9	48	27·8	82	46·7	116	65·5	150	84	183·2	103	217·4
9	48·2	28	82·4	47	116·6	66	150·8	84·4	184	103·3	218
9·4	49	28·3	83	47·2	117	66·1	151	85	185	103·9	219
10	50	28·9	84	47·8	118	66·7	152	85·5	186	104	219·2
10·5	51	29	84·2	48	118·4	67	152·6	86	186·8	104·4	220
11	51·8	29.4	85	48·3	119	67·2	153	86·1	187	105	221
11·1	52	30	86	48·9	120	67·8	154	86·7	188	121	250
11·7	53	30·5	87	49	120·2	68	154·4	87	188·6	150	302
12	53·6	31	87·8	49·4	121	68·3	155	87·2	189	204·4	400
12·2	54	31·1	88	50	122	68·9	156	87·8	190	250	482
12·8	55	31·7	89	50·5	123	69	156·2	88	190·4	300	572
13	55·4	32	89·6	51	123·8	69·4	157	88·3	194	400	752
13·3	56	32·2	90	51·1	124	70	158	88·9	192	500	932
13·9	57	32·8	91	51·7	125	70·5	159	89	192·2	600	1112
14	57·2	33	91·4	52	125·6	71	159·8	89·4	193	700	1292
14·4	58	33·3	92	52·2	126	71·1	160	90	194	800	1472
15	59	33·9	93	52·8	127	71·7	161	90·5	195	900	1652
15·5	60	34	93·2	53	127·4	72	161·6	91	195·8	1000	1832
16	60·8	34·4	94	53·3	128	72·2	162	91·1	196	1250	2282
16·1	61	35	95	53·9	129	72·8	163	91·7	197	1500	2732
16·7	62	35·5	96	54	129·2	73	163·4	92	197·6	1750	3182
17	62·6	36	96·8	54·4	130	73·3	164	92·2	198	2000	3632
17·2	63	36·1	97	55	131	73·9	165	92·8	199		
17·8	64	36·7	98	55·5	132	74	165·2	93	199·4		
18	64·4	37	98·6	56	132·8	74·4	166	93·3	200		
18·3	65	37·2	99	56·1	133	75	167	93·9	201		

To convert Fahrenheit into Centigrade, subtract 32, multiply by 5, divide by 9; Centigrade into Fahrenheit, multiply by 9, divide by 5, and add 32.

CHAPTER V.—ELECTROTYPING.

OUTLINE OF PROCESSES—MATERIALS FOR PROTECTING SURFACES—PREPARATION OF POROUS SURFACES, PROCESSES 1 TO 5—NON-POROUS SURFACES, PROCESSES 6 TO 8—*RESUMÉ*—MOULDING MATERIALS—GELATINE—PLASTER—CASTING IN PLASTER FROM GELATINE—FROM PLASTER—GUTTA-PERCHA MOULDS—MOUNTING—METALLISATION OF GUTTA-PERCHA COMPOSITION MOULDS—OBSERVATIONS—PREPARATION OF METAL SURFACES EMPLOYED AS MOULDS—METALLISATION OF ARTISTS' WAX ORIGINALS—EQUIPMENT OF GUTTA-PERCHA COMPOSITION MOULDS.

OUTLINE OF PROCESSES.

ELECTROTYPING is depositing any metal (usually copper) from a suitable solution, with a properly regulated current, on to a mould or matrix, until the deposited metal has acquired a sufficient thickness to enable it to be bodily removed from the object upon which it has been deposited.

It comprises broadly the following processes:—

1. Obtaining a mould of the object to be reproduced.
2. Preparation of the surface of the mould to enable it to receive a deposit.
3. Depositing the metal upon the mould.
4. Removing the type from the mould, and suitably finishing it for its intended purpose.

A first and important consideration in connection with electrotyping is the mould, the material of which it is made, and the means of obtaining a suitable mould from any given object.

An ideal moulding material for all art work would be one which has the three good qualities of the gutta-percha composition, viz. faithfulness of cast, ease of metallisation, and non-attackability in bath, united with the only useful feature of the gelatine composition (viz. elasticity); wanting this, the best use must be made of what exists.

The following materials and compositions, more or less good in particular circumstances, can be employed for obtaining moulds for electrotyping purposes:—

Plaster-of-Paris: usually employed as a go-between for obtaining a mould in gutta-percha or gelatine composition from materials that cannot withstand the application of these compositions direct. It is not usually employed as the material of a mould to be put into the electrotyping vat.

Gelatine composition: used for obtaining moulds of undercut work, employed when necessary as a moulding material to be immersed in the electrotyping vat; also used as a go-between for obtaining gutta-percha moulds.

Gutta-percha composition: employed for obtaining moulds direct of objects from which the mould will draw, and from objects with undercut work by the aid of the two above materials. This is the best moulding composition for immersion in the bath.

Compositions of bees'-wax, Venice turpentine, litharge, etc.; employed principally for obtaining moulds of type, wood-engraved blocks, etc., for printing purposes.

Electrotype moulds are employed for low relief work when great numbers of copies are required. They are also employed for strip moulds for high relief work, in which case they are made very thin, so as to enable them to be torn or stripped away from the copper reproduction of the original. Metal moulds are also required for electrotype silver reproductions.

The properties that determine a good moulding composition for electrotyping work are:—

A material or composition that will give a perfect impression of the object to be copied.

(Any one of the above satisfies this requirement.)

A material or composition that can be easily and perfectly "metallised."

(Gutta-percha composition is the one that best fulfils this, although, as will be shown, the others can be metallised.)

A material or composition that is not attacked by the bath. Again, for the acid copper solution the gutta-percha composition is the only one that is not attacked, the solution on the contrary acting as a preservative. For alkali baths, such as silver, metal moulds or "clichés" are alone available.

There is a fourth property requisite to enable all possible objects *to be moulded direct*—viz. elasticity. Gelatine composition alone has this quality, and in many cases this material will be used notwithstanding the extra trouble entailed by its employment.

The gutta-percha composition has, when freshly prepared, considerable elasticity; it can be sprung (without distortion) from objects that are considerably undercut, but it is necessary for the undercut to be bold; if it is too trivial, the small projecting pieces on the mould will get strained past recovery, if not broken. Practice with the material will show how much undercut this composition can be safely sprung from.

Indirectly it is possible to obtain a mould in gutta-percha composition from any object, however greatly undercut, by what is called the waste plaster process, which consists of taking a gelatine mould from the work to be reproduced, and from the mould taking as many plaster casts as copies of the original are required.

These plaster casts serve as originals for obtaining the gutta-percha composition mould, from which they are chipped or broken out, being for this purpose cast as thin as is conformable with safe handling.

In the following pages the work for moulding processes is classed under the four following heads:—

(A) Objects that have only one face or side that requires to be copied, the work on which will allow a mould to leave freely.

(B) Similar objects, but so undercut as to necessitate an elastic or waste mould.

These two comprise all such objects as plaques, dishes, inkstands, moulding frames, finger plates, door knobs, etc.

(C) All objects that have more than one side or face to be copied, necessitating a two- or more part mould, but from which it is possible to take the mould direct without resort to elastic or waste moulds. Among these are vases, lamps and lamp-stands, bases of all kinds, and some simple figure subjects.

(D) All complicated art bronzes which require a mould to be taken in two or more pieces, with a possible resort to waste mould processes.

Detailed, the operations of moulding are thus:—

(i.) The mounting or fixing up of the object in a convenient manner for moulding.

(ii.) The preparation of the surface of the object to prevent the sticking of the mould.

(iii.) The casting or application of the moulding material.

As regards the operations enumerated above, the mounting and the dividing up are the only ones which to any great extent must be left to the judgment of the operator, as they depend on the contour of the object to be copied. Examples are given later on, covering a great variety of work.

The preparation of the surface varies only slightly for difference of materials cast from and materials cast with, so that all cases can be enumerated.

The casting or application of the moulding material is also nearly the same, whatever the object being copied.

Although the routine given above is in the actual order of the operations, it will be preferable, to save speaking of operations that have not been previously explained, to start at No. ii. first, then describe No. iii., and finally No. i.

MATERIALS USED FOR THE PROTECTION OF SURFACES.

By protection of surfaces for moulding is meant the preparation of the surface of the work being moulded or cast, so that the mould or cast will leave it freely without injury either to itself or the work.

Every object or every mould from which moulds or casts have to be taken must have its surface suitably protected —*i.e.* painted with some grease or varnish that will ensure the safe leaving of the mould or cast.

Excepting gelatine composition, which requires special treatment, all materials can be classed for this purpose as porous or non-porous, the first-named being the more troublesome to prepare.

Plaster-of-Paris, wood, and fabrics are examples of porous materials, and metals, china, ivory, etc., illustrate the non-porous.

This subject is treated as follows: First, the composition of the various greases, varnishes, etc., employed for the above purpose; then are given processes for preparing surfaces of plaster-of-Paris, the most frequently used of the porous materials; next the preparation of wood, fabrics, and similar materials; then the preparation of the surface of gelatine composition, a material by itself; finally, the non-porous materials, comprising metals, china, ivory, and similar materials.

No. 1.—Dissolve by heat 4 oz. bladder lard, 1½ oz. of stearine wax cut fine, 1 fluid oz. of rape oil, and sufficient paraffin oil so that the composition only just stiffens when cold.

No. 2.—Same as above, excepting that no paraffin oil is to be employed, the lard and wax to be dissolved in sufficient lard or rape oil.

Russian tallow can take the place of the lard in the above greases. In both cases sufficient oil is to be added so that the composition only just sets when cold.

No. 3.—Good Judean asphalt is crushed and dissolved in mineral naphtha to the consistency of thin syrup.

It can be prepared by two-thirds filling a wide-mouthed bottle with naphtha, and adding the crushed asphalt until the bottle is filled to the neck. It is then corked and well shaken from time to time. If necessary, dissolution can be hastened by standing the bottle uncorked in a saucepan of boiling water.

This is to be kept as the stock from which small quantities at a time are taken and more or less diluted with naphtha, according to the work in hand.

This varnish should be as much as possible protected from the light by keeping in a dark coloured glass or stoneware bottle.

No. 4.—Brown hard varnish.

No. 5.—The varnish as above, but very much thinned by the addition of methylated spirit.

No. 6.—Oil of turpentine.

Brushes well suited for the application of the above greases, varnishes, etc., are badger and fitch hair of various sizes, according to the work in hand. Convenient brushes are shown in Fig. 94.

The badger hair is of a most suitable stiffness for varnishing and polishing purposes (some are shown at Fig. 94); and for grease paintings, dusting, etc., the French hair brushes made specially for moulders are the most convenient.

PREPARATION OF POROUS SURFACES.

Plaster-of-Paris is the most generally useful of all the materials that are employed for moulding or reproducing work. Its surface can be prepared as follows.

The preparation of plaster surfaces, when employed as object for obtaining moulds or casts in gutta-percha composition, gelatine composition, plaster-of-Paris, etc., is a method of stopping the porosity of the plaster without in the slightest degree filling up or blunting the details of the work upon it.

PROCESS NO. I.

The entire surface of the thoroughly dried plaster-of-Paris object is to be gently given three or four abundant coatings of the varnish (composition No. 3, page 140, diluted) one after the other, as soon as the preceding one has soaked in; then heated in an oven, and kept at a temperature not higher than can be freely handled (from 30° to 40° C.) to drive off all the free naphtha. It is then allowed to cool—preferably in the oven, as it is liable to fly if brought into contact with the cold air. The entire surface has now to be gone over again with the brush, kept continually but only slightly charged with the varnish, moving the brush briskly and repeatedly in every direction until the varnish is brought to the surface. It is now allowed to dry and harden, exposing it to plenty of light—to the sun, if possible, when a brilliant polish is to be given to it by vigorous and repeated brushing with a dry, stiff-haired brush. The entire surface must be made to shine, but with the shine of "elbow grease," not varnish. Note that when the plaster has had its first coatings of varnish its surface is considerably hardened, and will stand without injury a brushing that would ruin plaster not so treated; but nevertheless the strength of brushing must be regulated with discretion.

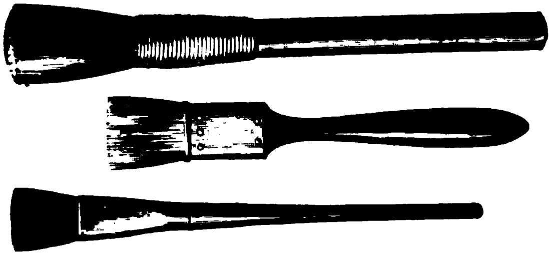


FIG. 94.—BADGER AND FITCH BRUSHES FOR VARNISHING AND POLISHING.

Some practice is necessary to bring the varnish to the surface without dissolving previous coatings or making the surface of the plaster gummy; it is absolutely necessary for good work that the varnish should only be just brought to the surface and then polished; the varnish must be beneath, and not upon, the surface. Should it get sticky and the brush tend to drag, on the work, the excess varnish must be washed away with naphtha, the work dried, and the polishing started afresh.

The hardness or porosity of the plaster surface to be treated may vary considerably, either owing to the quality of the plaster employed, the material of the mould from which it was cast, the manner of casting, or through burning by having been submitted to too great heat when drying, etc.

Should the face of the plaster from any cause be very porous, and a good surface difficult to obtain, the following method can be resorted to. The entire surface of the plaster is to be given four or five abundant coatings of the asphalt varnish, the naphtha evaporated, and the plaster allowed to cool as before. Should there be any hard places where the varnish refuses to soak in, it must be cleaned off with a rag moistened with naphtha. The entire surface can now be gone over with a light coating of brown hard varnish (very much diluted with methylated spirit), care being taken that it all sinks below the surface of the plaster. Should there be any places where it refuses to sink, it must be wiped away with a rag moistened with methylated spirit. This coating has to be allowed to dry, and then a surface and polish is to be given with the asphalt varnish as before described. By this interposition of a coat of spirit varnish the first coatings of the asphalt varnish are protected from the solvent action of subsequent coatings, and thus a good surface can be more rapidly given to very porous plasters.

As stated before, it is only necessary to employ this intervening coat of spirit varnish when the plasters are bad. Good plasters cast from jelly, metal, sulphur, and similar moulds, will very often only absorb one thin coating of the asphalt varnish before it can be brought to a surface. Especially is this the case when a small quantity of alum solution has been added to the water in which the plaster was mixed.

The asphalt varnish can be employed much thicker for porous plasters and first applications than for sound plaster, and for finally bringing to a surface.

Note.—If the surfaces of plaster casts are rubbed or cut whilst still wet, the parts so touched will be harder than surrounding portions. The contrary is the case if the surface is broken when the plaster is quite dry. Those portions are then more porous than the surrounding parts.

PROCESS NO. 2.

This process is principally used for plaster-of-Paris moulding-cases or shells. For such work all that is necessary is that the porosity or suction of the plaster shall be stopped. There being no work to preserve, a polish can be given by actually varnishing the surface of the plaster. In that case it is of no consequence if the plaster is wet or dry.

The working surfaces of a plaster case are given three or more abundant coatings of the French polish, one coating being given time to dry before applying another, and the several coatings must be applied as rapidly as possible to avoid disturbing previous coatings. This is to be continued until a uniform brilliant surface is obtained.

This method is a great deal more rapid than the previous one with the asphalt varnish, and the result is different in that the polish is obtained by a layer of varnish above the surface of the plaster, similar to varnishing wood, etc.; whereas in the first method the surface of the plaster itself may be said to be polished.

PROCESS NO. 3.

The process about to be described is a splendid hardener and preservative of the plaster. It is rather expensive in time, and is principally intended for valuable plaster piece moulds, from which castings in plaster-of-Paris only are to be taken.

PREPARATION OF PLASTER PIECE MOULDS.

The mould, when thoroughly dried, is taken apart, and each separate piece is freed from all dust and grit by means of a soft brush, after which it is carefully put together again and strongly bound up with cord. The entire mould is then put into a gas oven and warmed to a temperature that can be comfortably handled (30° to 40° C.), when it is filled with boiled oil that has been heated to about the same temperature. The mould, still filled with the oil, is replaced in the oven and kept at the above temperature for an hour or so, all the time keeping it well filled by adding oil from time to time to replace that absorbed.

When the absorption of the oil has become very sluggish or ceased altogether, the gas is turned out and the oven allowed nearly to cool. The mould is then to be removed, the oil emptied out, and the mould allowed to drain. It is again replaced in the oven (and stood in such a position that any free oil can drain away) for half an hour or so, at the same temperature as before, and after being allowed to cool it is taken to pieces. All unabsorbed oil on each piece is carefully mopped up with a soft flannel pad and the mould put away in a warm place, free from dust, for three or four days, to allow the oil to thoroughly harden. After this the face of each piece is dusted, and then by means of a soft brush painted with the oil (warmed) as long as it is absorbed, particular notice being taken that the brush is not dragged or scraped over the edges of the pieces; the brush must leave the surface of the pieces by the edges, not start from them. Attention to this point is necessary for two reasons—firstly, so as not to dull the edges, which, in some cases, are very delicate; and secondly, to prevent thickness of oil on the abutting edges, which keeps the pieces from registering truly when the mould is put together. After the above final painting with the oil, they are allowed to harden for a day or two, when they can be given a splendid polish by gentle rubbing with a soft flannel pad, care being taken as before with the edges. The surface of the pieces should then present a uniform bright appearance. Should there be any dull patches, those parts must be gone over again with the oil.

Note.—Care must be taken to make neither the plaster nor the oil too hot, or the surface of the plaster mould will be softened instead of hardened.

PROCESS NO. 4.

The process described below is employed when taking plaster casts from plaster moulds, for preparing adjacent surfaces when making plaster piece moulds, and in all cases when wet plaster, with work upon it, serves as the material to be cast from.

The wet plaster surface is flooded with turpentine until it no longer sinks in, the surplus turpentine being mopped up with a brush kept continuously dry by wiping on a rag. No free turpentine must be allowed to remain on the surface of the plaster, which should have a dry, brilliant appearance. If it shows any dull patches, the greasing of those parts must be repeated.

PROCESS NO. 5.

Objects of wood and fabrics for moulding from are to be given five or six abundant coatings of the asphalt varnish (No. 3, page 140, diluted), care being taken that the material entirely absorbs the varnish in every part. It can be allowed to dry in the open, or, to hasten it, it can be put in the oven and kept at about 35° to 40° C., until all the naphtha is driven off, when a brightness can be imparted to the surface by a continuous gentle brushing with a medium brush.

The above process is simply intended to saturate the texture of the material without filling up the pores, as happens in the case of plaster. Hence the necessity of having the varnish absorbed by the material before allowing it to dry, as it is requisite that every variation of surface in the texture of the material should be reproduced in the electrotype.

PREPARATION OF NON-POROUS SURFACES.

PROCESS NO. 6.

GELATINE FOR PLASTER-OF-PARIS.

The gelatine composition can be classed as a non-porous material, although on account of its sensitiveness to both heat and moisture it must have its surface prepared in a manner peculiar to itself.

A gelatine mould, on removal from its object, has a greasy surface, which is to be removed by freely brushing it with a soft brush kept plentifully charged with French chalk. The chalk must be made to penetrate into all details of the work, so that it shall mop up every trace of grease. This having been properly done, all the loose chalk is brushed and shaken out of the mould, the surface of the gelatine then having a soft, dull, whitish appearance. The next operation is to give the gelatine mould a hard skin in the following manner. The entire face of the mould is sprayed with a tepid semi-saturated solution of chrome alum and water until every portion is damp. It is then rapidly gone over with a soft brush, also charged with the alum solution, so as to loosen the chalk and enable the alum to attack the jelly. The entire mould is then freely rinsed with the alum solution to wash out as much remaining chalk as possible. The superfluous alum solution is finally shaken and brushed out, and the mould thoroughly dried with a soft brush and rag. This operation of hardening with the alum must be gone through very rapidly, while endeavouring to keep the face of the jelly uniformly moist. Care must also be taken that the alum solution is made to penetrate every detail of the mould.

The result of this treatment with alum is to harden the surface of the jelly to a greater or lesser thickness, which to some extent is less subject to heat and moisture than the jelly not so prepared. The skin can be made thicker and harder by repeating the process, or by using stronger oxidisers, such as ferric ammonia, alum, etc., but it is at the expense of the elasticity of the jelly, and perhaps loss of sharpness of the work, especially in fine work, when this alum treatment is a most delicate operation.

PROCESS NO. 7.

VARNISHING OF METAL, CHINA, IVORIES, AND SIMILAR MATERIALS FOR GUTTA-PERCHA COMPOSITION.

The object to be varnished is flooded with the asphalt varnish (composition No. 3, page 140, very much diluted), the excess being allowed to drain back into the jar. Then, with a medium hard brush, the varnish that is held by the hollows, etc., is mopped up, the brush being dried from time to time on a soft, dry rag. This is continued until all the excess varnish is removed, leaving a uniform thin layer of varnish; then, with the same brush, the entire surface of the object is briskly and continuously brushed in every direction until the naphtha has evaporated, leaving a thin film of varnish evenly distributed over the surface of the work. The thickness of the coating depends on the substance of the varnish, as only the thinnest film is necessary, requiring the varnish to be very dilute. When properly done, the coating of varnish should not be perceptible, and should not clog or dull the finest work. Should the brush drag, or the surface have a streaky appearance, the varnish must be washed off with naphtha, and the process started afresh with a more dilute varnish.

PROCESS NO. 8.

PREPARATION OF METALS, CHINA, IVORIES, AND SIMILAR MATERIALS FOR GELATINE COMPOSITION AND PLASTER-OF-PARIS.

For this purpose all that is necessary is that the work shall be given a thin uniform coating of grease composition No. 2 (page 140). The entire surface of the object has to be gone over with a brush very lightly charged with the grease. Care is to be taken that no portion of the surface is missed, and that there are no thicknesses left on the edges, etc. The surface, when greased, must present a uniform brightness, free from smears. It will be found convenient to employ two brushes, one to apply grease, and a second dry one to remove the excess, as it must be remembered that it is only the thinnest possible film of grease that is required.

The simplest method of suitably charging the grease brush is to roll the brush round the inside of the pot, so that it is well greased, and then to pull it two or three times through the thumb and finger of the left hand, well squeezing it at the same time. If the grease that leaves the brush is dirty, repeat with more grease until it leaves the brush clean. This not only cleans the brush, but by squeezing out as much grease as possible, the brush is left thoroughly greased, but with no free grease to be caught up in the hollows, etc., of the work.

The above eight processes are to be employed thus :—

For casting or moulding with *gelatine* from objects made of the materials enumerated below, it is requisite that their surfaces should be prepared as follows :—

Objects of metal, ivory, china, and all non-porous materials that will withstand a temperature of 40° C. must have their surfaces prepared as described in Process No. 8, employing the grease composition No. 2.

Objects or moulds of plaster-of-Paris must have their surfaces prepared as described in Process No. 1, and painted as described in Process No. 8 with grease composition No. 2.

Plaster-of-Paris moulding cases and similar work are to be prepared as described in Process No. 2, and painted as described in Process No. 8 with the grease composition No. 1.

Woods, fabrics, and all similar materials whose surface texture is to be preserved, are to be prepared as described in Process No. 5, and painted as described in Process No. 7 with the grease composition No. 2.

Gelatine composition casts or moulds are to be prepared as described in Process No. 6 (only employing a saturated ferric ammonia alum solution in place of the one given), and painted as described in Process No. 8 with the grease composition No. 1.

Wax and clay surfaces are to be given a very thin and even coating of French polish with a soft brush, and after hardening, painted as described in Process No. 8 with the grease composition No. 1.

For casting or moulding with *plaster-of-Paris* from objects or moulds made of the materials enumerated below, it is necessary to prepare their surfaces as follows :—

Gelatine composition casts or moulds are to be prepared as described in Process No. 6, and painted as described in Process No. 8 with the grease Composition No. 1.

Note.—The surface of the gelatine has been properly prepared when, on removing a cast from it, the surface of the mould presents a brilliant appearance, as though it were quite unnecessary to re-grease. If an excess of grease has been applied, the edges of the plaster cast will show dull. A want of proper protection of the jelly surface is shown by the face of the mould presenting a dull, whitish appearance on removal of a cast, with, perhaps, swellings on the flat surfaces.

Metals, china, ivory, and all non-porous materials must have their surfaces prepared as described in Process No. 8 with the grease composition No. 2.

Plaster-of-Paris casts or moulds must have their surfaces prepared as follows:—

When taking plaster casts, or moulds from plaster surfaces that are dry, and which require the details of the work upon them to be preserved, they must be prepared as described in Process No. 1, and painted as described in Process No. 8 with grease composition No. 2.

For stopping the porosity of plaster cases and similar work (wet or dry) prepare them as described in Process No. 2, and paint them as described in Process No. 8 with grease composition No. 2.

Plaster piece moulds can be prepared as described in Process No. 3, and painted as described in Process No. 8 with the grease Composition No. 2.

Note.—This process can be employed in place of Process No. 1, for this purpose—viz. casting plaster from plaster.

When casting from plaster waste moulds or for piece moulding, and in every case when casting from plaster objects or moulds that are wet, and the details of the work upon which have to be preserved, prepare the surfaces as described in Process No. 4.

Wax and clay surfaces are prepared by giving with a soft brush a very thin coating of soap solution.

For casting or moulding moulds with the *gutta-percha* composition from objects or moulds made of the materials enumerated below, the surfaces must be prepared as follows:—

Plaster-of-Paris casts or moulds are to have their surfaces prepared as described in Process No. 1.

Plaster-of-Paris cases and similar surfaces, where there is no work to be preserved, can have their surfaces prepared as described in Process No. 2.

Gutta-percha composition surfaces must be painted with the soap solution No. 6.

Wood, fabrics, and all similar materials whose surface texture has to be preserved, must have their surfaces prepared as described in Process No. 5.

Metals, ivories, and all non-porous materials must have their surfaces prepared as described in Process No. 7.

For casting or moulding with wax from objects or moulds made of the materials enumerated below, the surfaces of the objects or moulds must be prepared as follows:—

Gelatine composition moulds or casts have to be prepared as described in Process No. 1.

Plaster casts or moulds are to have their surfaces prepared as described in Process No. 1, and painted as described in Process No. 8 with grease composition No. 2.

Metals, ivories, china, etc., are to be painted as described in Process No. 8 with grease composition No. 1.

PREPARATION AND USE OF MOULDING MATERIALS.

PREPARATION OF THE GELATINE MOULDING COMPOSITION.

Gelatine of good quality—Nelson's No. 3 is a good tough gelatine for this purpose—is to be steeped in cold water until it becomes flaccid. The sheets, as they become limp, are removed from the water, drained, and put into the melting pot, in which has already been put the correct quantity of glycerine (4 fluid oz. of glycerine to every lb. of gelatine). Whilst melting it is occasionally stirred until all traces of lumpiness have disappeared, and the composition has become of a uniform consistency.

As little water as possible should be added to the jelly, as it should be worked as stiff as is consistent with its running into all the details of the work ; if it is considered too stiff, water can be stirred in whilst melting until it is of the desired substance. A little practice with the composition soon shows at what consistency it can be worked for the job in hand ; it can be used heavier for bold work than for jobs with delicate, high relief work, which would not withstand the strain of separation if the composition were too stiff.

Gelatine alone can be used, but by the addition of glycerine the drying and consequent shrinking of the mould is retarded.

SOME HINTS FOR USING AND MOULDING THE GELATINE COMPOSITION.

For all but very small work the gelatine composition must always be used with a case, on account of its flexibility. Moulds taken with it without a supporting case are certain to be distorted.

The melting pot for the composition should be a water-jacketed vessel ; failing this, a small pail or saucepan stood inside a larger one will serve. The inner pot, containing the composition, should be kept covered whilst the composition is melting, so as to prevent loss of water by evaporation and the consequent formation of a more or less insoluble scum on the top of the composition, due to oxidation by exposure to the atmosphere.

The temperature at which the composition is poured depends somewhat on the work in hand. As the work in jelly invariably demands a moulding case or shell, it is necessary to pour it at a not too high temperature or it will be impossible to separate the case without danger of breaking the jelly. When working with a case, the highest temperature the jelly may be poured at with safety is 45° to 50° C. A rough test of temperature for safe pouring is when the finger can comfortably be immersed and retained in the jelly (by first greasing the finger, adherence of the jelly will be prevented).

If the work being moulded is metal, and it is not possible to warm it before running the jelly, as high as possible a temperature must be risked. For plaster objects it can be run at a temperature which the finger can comfortably bear.

For wax and jelly the temperature must be brought down to 25° or 30° C. This can be done by removing the inner pot from the water bath, and keeping the composition continually and well beaten up until it has fallen to the desired temperature. In all cases it must be thoroughly beaten up before being poured into the mould.

Next to be considered after the temperature is precaution against air blebs. The cooler the jelly is poured, and the more intricate the work, the greater, of course, is the danger of air blebs. To minimise the risk as much as possible, the following precautions can be taken. When possible, always let the work occupy the lowest position in the case, so that the face of the mould is at the bottom. The work is not so liable to imprison air in the first case as the second, also the face of the mould will be more uniformly sound. Secondly, when the jelly is being poured into the mould it should be kept in one continuous flow until the mould is full, as fast as possible without choking the pouring hole. Afterwards it must be well shaken, being banged down on the bench whilst the case is held in the best position for the escape of imprisoned air. Lastly, and most important, just before the case is bound up for pouring the mould, the work, especially the hollows, should be sprayed with a solution of methylated spirit and hot water in equal quantities. If there is any French polish about, hot water alone must be used. This will break the skin that forms on the jelly as soon as it comes in contact with the air, and as on spreading over the work it rolls over and over, it is this skin that comes first in contact with the work, and is thus liable to spread over instead of entering small details, but on coming in contact with the moisture it breaks, and allows the unchilled jelly to escape, giving a better chance of a sound mould.

A funnel of clay, or preferably of metal, is fixed, by binding with clay, over the pouring hole, which should occupy the highest position on the cover of the case. This serves as a guide for pouring; also being filled up with the composition, it lends some pressure to drive the jelly into the mould, and also to take what shrinkage there is whilst cooling. The inside of the funnel, if of clay, should be French polished to prevent sticking. If there are vent holes in the case they are to be closed with a piece of clay directly the jelly shows itself through them.

Care must be taken, before the jelly is poured, that the plaster case has a perfectly brilliant surface (as described in Process No. 2, "Preparation of Surfaces"), or it will be impossible to open it when the mould is cold without damage to the object being copied or to the case.

No attempt must be made to separate the case before it is certain that the jelly composition is perfectly cold. When removing jelly composition moulds from their objects, or from casts that have been made in them, gently ease all round the edges first, and entirely loosen the mould from its object or cast before finally lifting it away. The moulds on removal from the object should be immediately replaced in their case, which keeps them rigidly to shape. Further, on account of drying, and consequent shrinking, the gelatine moulds should not be separated from the work until it is convenient to proceed straight away with the work for which they are intended; if a mould not finished with has to be left, it should be replaced on its object and bound up in its case.

The walls of the gelatine moulds employed for casting plaster from should be cast as nearly as possible of a uniform thickness, no matter what the variations of height of the object being copied; so that it should be as free to bend at one part as at any other, to prevent undue straining at any particular part. The thickness of the walls of the mould depends somewhat on the size of the object to be copied, being thicker for large work, from ⅝" to 1¼" thick according to the work.

MOULDING IN PLASTER-OF-PARIS.

PLASTER-OF-PARIS.

As this material expands on setting, it can only be employed direct to take casts or moulds from work that has no suspicion of undercut.

For obtaining moulds or casts in plaster-of-Paris from high relief or undercut work, resort must be made to an intermediary, such as gelatine, wax, or plaster piece moulds.

It gives most perfect impressions, and is one of the most generally useful of the moulding materials.

For general work it is advisable to use only fine plaster, costing about 3s. per cwt.

It is mixed for use in the following manner:—In an earthenware bowl is put as much water as is judged sufficient for the work in hand, and into this the plaster is graded through the fingers equally all over the surface until it rises level in every part with the water (or plaster is added until the water is just submerged), when it is beaten up into a uniformly stiff cream, free from all traces of lumpiness. In this condition it is ready for use.

By grading the plaster into the water it is not intended to be too finely divided; all that is necessary is that it shall fall into the water in a loose state, not having the particles more or less bound together, as this causes lumpiness and labour in beating up. To beat up, the spoon is kept well below the surface of the plaster and given a short, sharp, circular motion that makes the paste circle round, and brings every portion of it successively under the spoon.

Before commencing to beat up, the plaster should be level with the surface of the water in every part. When once stirring up has commenced, no more plaster should be added. If the above instructions are followed, the paste will be of the right consistency for working. It is preferable to add an excess of plaster than not enough, as there is no inconvenience in stirring in more water if the paste is too thick.

The paste should be made thinner for large work that requires more time to cast. A too continuous beating up of the plaster paste, or thinning it by the addition of water after it has commenced to set, must be avoided, as it will never set so hard as if sufficiently mixed and applied straight away to the work.

CASTING IN PLASTER FROM JELLY MOULDS.

With plaster, as with all casting or moulding operations, the chief trouble is to make the material, whatever it is, penetrate into every detail of the mould, so as to obtain sound casts without air blebs, etc.

EXAMPLE I.

From jelly moulds of plaques, dishes, and such-like goods, where the back of the mould can be flat, with an open case, so that it can readily be removed and replaced, a sound plaster cast may be obtained in the following manner :—Some of the plaster paste is poured over the entire face of the mould, the excess plaster being drained back into the bowl, leaving only a thin layer over the mould. It is then lifted from the case and allowed to drop through a distance of some 4 or 5 feet, so that it strikes the floor flat on its back. It is then replaced in its proper position in the case, and sufficient plaster is poured in and well shaken down on the bench. The back is then levelled or finished off as desired, and allowed to set. The result of this dropping on the floor is that the plaster is irresistibly driven into every detail of the work without further trouble. It is necessary to drop it as horizontally as possible, so that it strikes the floor perfectly flat, otherwise the plaster will be thrown out.

EXAMPLE II.

For jelly moulds of high relief work that have not a flat back, but yet have open cases, or figure subjects to be cast in two or more pieces, and all similar work that has not closed cases, good plaster casts can be obtained as follows :—

The entire surface of the jelly mould is covered with the plaster paste, the excess being poured back into the bowl, leaving a thin coating of plaster all over the surface of the mould as before. This is knocked into the details of the work by taking the case containing the mould and striking it on the thigh of the left leg. Whilst it is held in suitable positions for forcing the plaster into details, more plaster is added where it is required and the operation repeated. In doubtful places, the plaster can be knocked in with a brush ; then, as the plaster thickens, it can be built up to the desired thickness with spoon and hand, finally trimmed with a knife, and allowed to set.

By putting the left foot on a low stool whilst standing, a suitable bench is made of the left thigh for the above purpose, allowing of good bangings without danger of breaking the plaster case.

The jelly mould is kept in the case during the shaking down by the case being held so that the fingers project over the edge on to the jelly.

Brushes used in plaster must be thoroughly rinsed in abundance of water before the plaster sets.

a few seconds another ladle of plaster is poured in, the operation repeated, and emptied again ; this is done two or three times, with banging afterwards. When the plaster commences to stiffen, ladles of

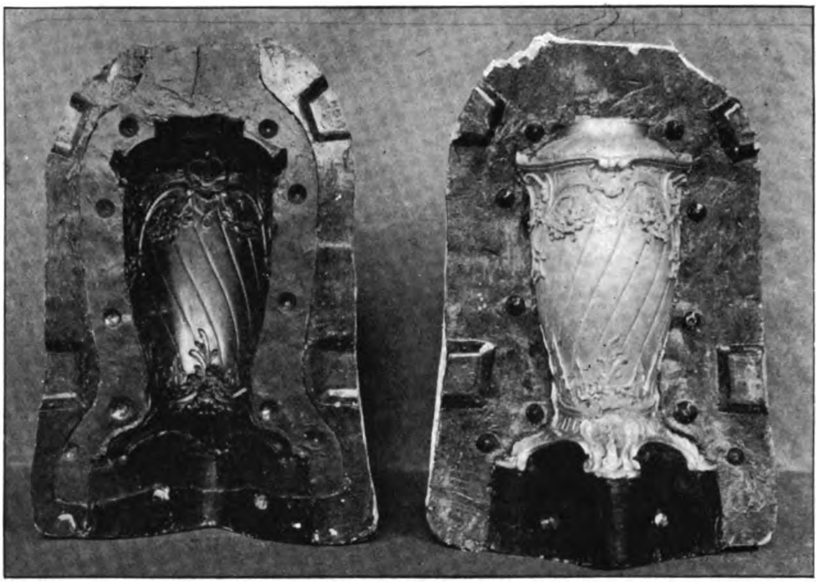


FIG. 95.—GELATINE TWO-PART MOULD OF LAMP-STAND IN PLASTER CASE, SHOWING STAND IN POSITION IN ONE HALF OF MOULD.

EXAMPLE III.

For obtaining plaster casts of figures in the round, and all objects that require a mould in a closed case (similar to that shown at Fig. 95), the procedure is as follows :—The case, containing the mould carefully placed in position to register, is securely bound up, stood on end, and a ladle or two of the plaster cream is poured in. It has then to be taken in both hands and swung round, so as to distribute the plaster over the mould, and then repeatedly banged on the knee (as for above example), whilst held in all positions, so that every portion of the mould successively has the plaster forced into it, always, of course, keeping the opening uppermost. The mould is then emptied of its free plaster into the basin. After plaster are put in and simply rolled round on the knee to distribute it evenly on the inside of the mould. This is repeated until the desired thickness is obtained, the operator finally trimming the base with a knife, and allowing the material to set. If required, the plaster can be built up over the base to close the opening.

In this manner plaster busts, figures, etc., can be cast as thin as desired for the waste plaster process.

For casting from plaster piece moulds the operation is exactly the same as above described.

CASTING IN PLASTER-OF-PARIS FROM PLASTER-OF-PARIS MOULDS.

A thin coating of the plaster cream is, with the hand or spoon, spread over the face of the plaster mould, and, by the combined action of shaking down on the bench and knocking in at doubtful parts with a brush, it is made to penetrate the details of the work. Sufficient plaster is then added to make the cast the desired thickness.

If the plaster mould should be too large and heavy to handle for shaking down, plaster cream can be taken in the hand and thrown, with considerable force, into all the details of the work; and, in doubtful places, it can be knocked in with a stiff brush as above, when sufficient plaster is added to make the cast the desired thickness.

When casting plaster waste moulds, only sufficient plaster cream is first mixed up to cover the work to a thickness of about ½″ and this is to be coloured by stirring in the water in which it is to be mixed some red ochre, or preferably ordinary washing blue, which has been previously worked with water into a stiff paste and squeezed through fine muslin to free it from grit. The remainder of the mould is built up with white common plaster. This is done to show when the object is approached on chipping the mould away. The coloured layer of plaster can be given a wash over with thin soap solution or clay water before applying the backing.

The examples given will, with the proper preparation of surface, apply to taking plaster casts from metal, china, wax, clay and gutta-percha moulds.

All the operations of plaster casting—viz. mixing the plaster, coating the mould, knocking and shaking down of it into the details of the same, and the final thickening up of the cast—should be executed without loss of time (or the plaster will set before completed), but not, of necessity, hurriedly, as the plaster gives plenty of time to perform all the operations properly without scamping the work of any.

HINTS FOR CASTING AND USING PLASTER-OF-PARIS.

STRENGTHENING WIRES.

For large cases, ditto plaques and dishes, figures, etc., it is necessary to use strengthening wires, which are to be buried in the plaster in such positions as will offer the most support to the work. Square section iron wire is very suitable for this purpose —⅛″, 3/16″, ¼″, ⅜″, etc., depending on the size of the work. If a mould or cast is intended to be kept, the iron wire must be protected from rusting (due to the dampness of the plaster) by coating it thoroughly with Brunswick black, or preferably by using galvanised wire. If this protection of the iron is not attended to, the discoloration of the plaster for certain, and possibly bursting, will occur. If it were not for the cost, brass wire would be best for this purpose.

The wires are to be bent to the shape of the work, and placed in a position that offers the best support to the cast or mould. They must be bent as near to the shape as will allow them to be well buried in a casting of normal thickness. They are placed in position between what may be called the first and second layer of plaster. The cast or mould is given its first layer of plaster all over to the thickness of, say, from ⅜″ to ½″. When this is stiff enough to support the weight of the wire it is placed in position, and then the plaster is built up to the desired thickness, completely burying the wire.

In all closed moulds where the opening is not sufficiently large to allow the bent wires to be passed, it is necessary to place them in position before binding up, and to prevent the wire coming through to the surface of the cast—that means, touching the mould—there are built on it small plaster balls in such positions that when in the mould they keep the wire from touching the sides.

As the wires are loose, a little care must be exercised whilst casting (especially if it is a plaster mould), when shaking down on the knee, to prevent the wire injuring the mould. As the coating of plaster thickens and gets stiff, the wire can be made to take the desired central position by means of pliers.

A piece of paperhangers' canvas is sometimes spread between the first and second layer of plaster, especially in flat work. It should be well damped before being placed in position.

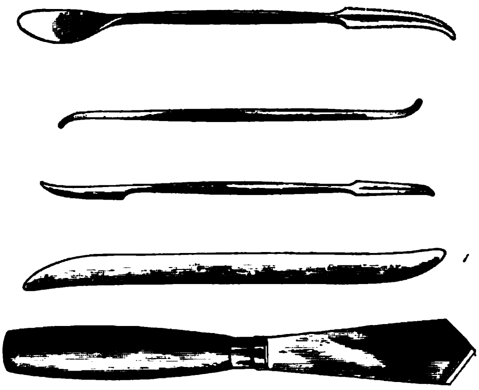


FIG. 96.—MOULDING TOOLS.

When casting plaster-of-Paris cases, covers, etc., and the greater portion of work in open cases, the plaster has to be built up by hand, as, however varied the outline of the work, it is desirable that the walls of the case or cast shall be as nearly as possible of a uniform thickness; thus, after the knocking in of the first thin coating of plaster, to make it penetrate details of the work and to prevent air blebs, a fairly thick layer of the plaster paste is spread all over the work, starting at the highest parts. It is allowed to rest until it commences to stiffen, when some more is put on to the high parts and this is again allowed to stiffen. As it runs off the high parts into the hollows, it must be brought up again, so as to keep it to an even thickness. This is continued, plaster added and kept in place, until the desired thickness is obtained. Finally, whilst the plaster is still soft, with a moulder's knife or small builder's trowel, it is scraped into shape, the operator cutting it away where too thick, building it up on the high parts and, wherever it is thought to be thin, cutting the extremities true and square. The whole is finally scraped smooth and regular with tools similar to those shown in Fig. 96.

The plaster-of-Paris should be kept in a dry place and exposed to the air as little as possible. To this end it should be stored in a galvanised iron bin or barrel with a well-fitting lid.

Should it be necessary to use stale plaster, a few drops of saturated alum solution can be stirred into the water before adding the plaster—about 2 fluid oz. to every pint of water employed. This will make the plaster set in normal time, which is important when casting from jelly moulds. It also hardens the face of the plaster.

As before stated, plaster expands on setting. In some cases this peculiar and good quality is inconvenient—in such a case, for instance, as plaster piece moulding, where, if the plaster is left to its will, every separate piece in expanding lifts its edge away from the work, entirely ruining the register. This expansion can be prevented by mixing the plaster in water containing lime. Some unslaked lime is powdered and stirred into a bucket of water; let there be an excess of lime. When using, stir this up, allow time for the heavier particles to settle, and then take equal portions of this milky solution and pure water; into this mix the plaster. This treatment is always necessary when using plaster in confined places, as the expansion is almost irresistible.

When casting in plaster from jelly moulds, it is necessary to remove the cast from the mould as soon as a rise of temperature of the plaster can be detected by the hand ; if this is not attended to, there is danger of softening the surface of the jelly, as good plaster on setting rises as much as 10° to 12° C.

Plaster casts are to be dried in an oven at a temperature not exceeding 50° C. The heat should be turned off as soon as they are dry, and they must be allowed to cool in the oven, as hot plaster brought into draughts is liable to fly.

MOULDING IN GUTTA-PERCHA COMPOSITION.

This is a composition admirably suited for moulds intended for electrotyping purposes; it gives splendidly faithful impressions (a mould of a grating, containing 1,420 lines to the inch, was taken with it without pressure, and as a grating, was as perfect as the original). When freshly prepared, it is considerably elastic, simple to metallise, and is not attacked by the bath.

The composition consists of pure gutta-percha, two parts; lard (which has been boiled in water to remove the salt), one part. The gutta-percha is to be cut into very small pieces and put into the melting pot, with the correct proportion of fat; heat is applied and the mixture kept stirred until the fat combines with the gutta-percha, and the whole mass becomes of a uniform stringy consistency, free from lumpiness. It is then ready for use.

The following precautions are to be taken in the use of gutta-percha composition :—The gutta-percha composition is preferably melted in a steam-jacketed pot; failing this, a sand bath will serve. It is necessary that the flame shall not come in direct contact with the pot containing the composition, for fear of burning it.

During the mixing the composition must be constantly stirred to prevent the gutta-percha from settling at the bottom of the pot and getting burnt while the fat floats on top; and also to get the fat and gutta-percha thoroughly incorporated at as low a temperature as possible. Subsequent meltings only require an occasional stir.

When melting the composition it should not be allowed to get to a higher temperature than 110° to 115° C.; if it gets hotter than this it burns, and its "life" (*i.e.* elasticity) is gone.

The composition is in a perfect working condition after its third melting, and its "life" at this stage considerably depends upon its being melted slowly and at as low a temperature as is consistent with obtaining sound moulds. With use it gradually loses life and consequent elasticity. It can be revived by addition of new gutta-percha, or kept for low relief work.

EXAMPLE I.

GUTTA-PERCHA COMPOSITION MOULDS FROM METAL.

The work to be moulded is heated in an oven to about 100° C., and with a stiff brush a thin layer of the composition is painted uniformly over its face, being made to penetrate the hollows and details of the work. It is then replaced in the oven and kept at a temperature not exceeding 110° C. for ten or fifteen minutes, when it is removed and sufficient composition poured on to bring it to the required thickness.

EXAMPLE II.

GUTTA-PERCHA COMPOSITION MOULDS FROM PLASTER-OF-PARIS.

If the work being copied is plaster, it must not be heated in the first instance above 60° C., at which point removal from the oven must be risked to allow of its being rapidly painted with the composition. It is replaced, and can be warmed up to 100° C. for a few minutes. It is then allowed to cool down in the oven to about 50° C., the composition in the pot also being allowed to cool at the same time, as the high temperature is only necessary to allow it to become sufficiently liquid to penetrate into details of the work.

The above preliminary coating and subsequent heating is for driving off all imprisoned air, and making the composition (which is somewhat stiff) penetrate into all the fine details of the work.

The thinner this first coating of the composition the better, as it will require less heat to make it penetrate into the work ; but care must be taken that every portion of the face of the object is covered.

A brush suitable for this work is the ordinary bristle scouring brush having not more than three rows, as a narrow one is preferable for this work.

EXAMPLE III.

For taking moulds in gutta-percha composition from objects that require cases, the following is the procedure :—The work is removed from its case, or if fixed, that portion of the case carrying it is heated and painted with the composition, and heated again as before described in Example I., page 153. It is then replaced in the case and securely bound up, a large metal funnel is fixed on the pouring hole, and sufficient of the composition poured in to fill the mould.

The funnel must be kept filled until the composition in the mould has cooled so as to take up the shrinkage ; the contraction of the composition in an open mould is slight in every direction, and consequently the copy is not actually as large as the original. When confined in cases the mould is, as regards size, a more perfect reproduction ; at any rate, the major portion of the shrinkage takes place at the pouring hole. For this reason it is necessary to keep the funnel full, and the composition in it liquid (by warming with a Bunsen flame), until it is certain that the composition in the mould has set. If this is not attended to, it will be sucked away from the work immediately under the pouring hole, leaving only a tissue over the work. The pouring holes of cases intended for gutta-percha moulding should be much larger than those intended for gelatine, not less than 3″ diameter, and the funnels should be correspondingly high to allow for the attendant shrinkage above mentioned.

MOUNTING OF WORK FOR MOULDING.

By mounting for moulding is meant some method of fixing or holding the object being moulded in a definite position, and the material of which the mould is made in bounds, whilst it is setting.

In the following pages there are given four typical examples of such mounting, which, with modifications, will embrace all possible work.

EXAMPLE I.

Metal objects not having a very great variation of height, and only one side to be copied, such as plaques, medallions, dishes, frames, etc., can be mounted in the following manner :—A hard-rolled copper band, of sufficient width and length, is bent into a circle (or oval, as the case may be) at least one inch larger in diameter than the object being copied, and is kept in bounds by binding wire circumferentially round it, as shown at Fig. 97. This ring is placed on a piece of sheet-iron of sufficient area, some plaster is mixed, as directed on pages 148 and 149, and banked all round inside the bottom

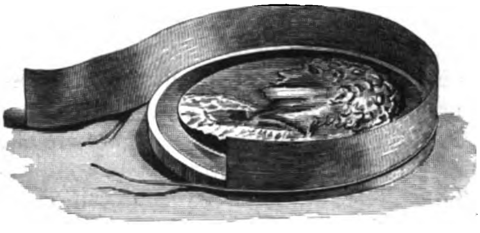


FIG. 97.—MEDALLION MOUNTED IN PLASTER SHOWING METHOD.

edge of the copper ring, after a shaking down to flatten the top. It is allowed to stiffen sufficiently to support the weight of the object, which is to be placed exactly in the centre and gently pressed down into it until the edge in every part has just sunk below the surface of the plaster. When the plaster has completely set, the binding wire is slipped off, and the copper band temporarily removed to enable it to be trimmed level with the edge of the object in every part, as shown in the sketch, Fig. 97. It has then to be dried in the oven, and its surface prepared as described in Process No. 1, page 141; the metal object as in Process No. 7, and the gutta-percha mould taken as directed in Example I., G.P. moulding, page 153. In Fig. 98 is shown a section of an object mounted as directed above, complete with the gutta-percha mould.

The fixing down with the plaster before described serves two purposes:—First, it makes a ground for bedding the work upon to keep the edges clean, and to prevent the moulding material from running underneath. Second, it provides an extra flange, or increases the size of the object to be moulded, which, for the following reasons, is requisite: First, if the mould is only the exact size of the object there is difficulty in handling for the necessary subsequent operations without damaging the edge, and in many cases it would be found impossible to trim up the type without injury to the edging of the work. Such a case is shown in Fig. 97, where the head edging would be certain to get damaged without this extra flange. Second, it enables the poorer quality metal of the type to be cut away, as it is the metal deposited at extremities that is generally of a more or less nodular and poor quality.

Plaster-of-Paris is employed for this fixing down on account of the heat requisite for gutta-percha moulding. For casting in gelatine or plaster, modelling clay can take its place.

The first type obtained can be left with its extra flange and employed as original for moulding from, in which case the copper band can be bound straight away upon it. The same with plasters when made for moulding purposes; they should be cast with the extra flange.

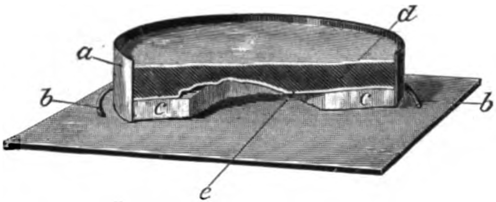


FIG. 98.—SECTION OF MEDALLION AND GUTTA-PERCHA MOULD; *a*, COPPER BAND—*b*, BINDING WIRE—*c*, PLASTER MOUNT—*d*, MOULD—*e*, MEDALLION.

For rectangular objects of the same class it will be necessary to use, in place of the copper bands, stout angle iron cut to various lengths, so as to serve for any rectangular object. See Fig. 99.

An extra flange can be given to rectangular work by surrounding it with strips of wood of a thickness corresponding to the desired width of the flange, and clamping them in place between the frame and the work.

EXAMPLE II.

The second example covers all objects that have still only one side to be copied, but, having such high relief work or great irregularity of surface, have to be moulded in a case if only to economise the moulding material. For gelatine composition, on account of its flexibility, a case is compulsory. The amount of variation of surface that requires a case, to some extent depends upon the size of the object to be moulded, as an irregularity in a large object might demand a case which would not be necessary if it were smaller. An example of this is shown in Fig. 100, which, being 27″ in diameter, calls for a

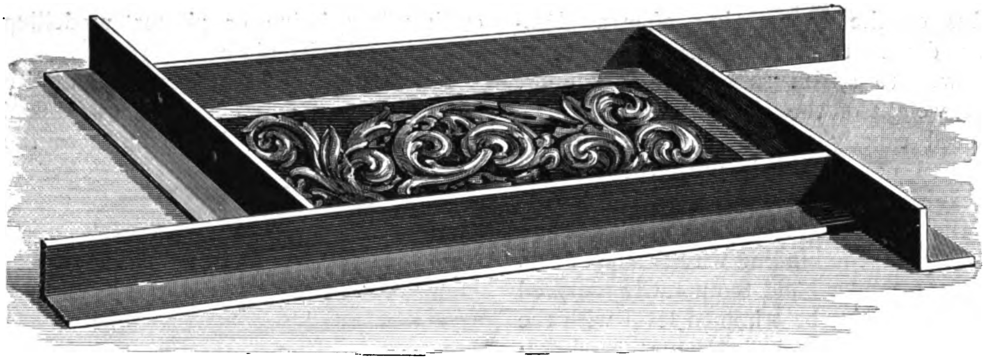


FIG. 99.—FLAT OBJECT SURROUNDED WITH STRIPS OF ANGLE IRON PREPARATORY TO BEING MOUNTED IN PLASTER.

case to economise the moulding material, which could be dispensed with if it were only 10″.

As in this example modelling clay will play an important part, it will be convenient to explain the general method of using it for case-making purposes. The grey clay most suitable for this work is that used for modelling purposes, the good quality of which has a very fine texture, free from all grittiness, and by smoothing with the finger it takes a beautifully smooth, soft surface. The commoner qualities may be good enough for case making, but they are gritty and unpleasant to work. Terra-cotta clay can also be used, but it does not equal for this purpose the ordinary grey clay above described.

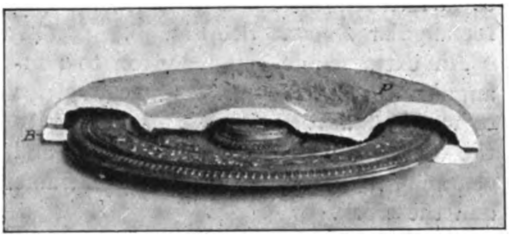


FIG. 100.—DISH MOUNTED, WITH PLASTER CASE, P, PARTLY CUT AWAY.

For use it has to be beaten up with water to a dough as soft as will allow of its being freely handled without sticking. It should be stored in a strong wooden box, and kept covered with wet rags. House flannel, folded to make three or four thicknesses, is very suitable, and if kept continuously wet will, with very occasional beatings up with water, preserve it in good working condition.

The principal purpose it serves in case-making is to make the space that is eventually to be occupied by the moulding material. The work being moulded is covered with a layer of clay of uniform thickness, which thickness represents the substance of the mould.

For thus covering the work the procedure is as follows:—A lump of the clay is taken and beaten up on the bench with the hands to a uniform dough. It is then rolled out into an elongated sausage, roughly of a uniform diameter, and of a size in conformity to the thickness of the covering desired. This is to be flattened by drawing over it three or four times, with slight pressure, a moulder's knife, held in both hands, the tip being held with the thumb and first finger of the left hand, the second finger serving with the bench as a guide to regulate the thickness. The knife is held slightly canted, the cutting edge being the lower. A good mechanical method of flattening the rolls when required to be of a very uniform thickness is to roll it out gradually between two strips of wood serving as gauges.

The dish D shown in Fig. 101 is the simplest example of this class, and can be mounted as follows:—It is placed face down on a sheet of iron or on a board, so as to be able to shift it about bodily. A flat ring of modelling clay, about 2" wide, is then rolled out as previously described, and placed right round the outside of the dish and tight against it. It must be sufficiently thick to reach the top edge of the flange, to which it is to be levelled by adding or scraping away clay until perfectly flat and true with it in every part, by use of the modelling tools shown in Fig. 96. There are then to be placed equidistant round the outer edge of this clay band three or four small pieces of clay for keys, cut from a strip of, say, ¾" wide by ⅜" thick. Lengths of about 1" to 1¼" long are cut from this strip, three sides of each piece being cut greatly on the bevel, and placed on the clay band in the position shown in the drawing at K. It is now ready for the plaster, which is mixed as directed at pages 148 and 149, and a layer to the thickness of about ⅛" is spread all over the clay band as at B, and extending some 2" on to the back of the dish, or it can cover the entire flange as far as the bowl directly the plaster is stiff enough to support the weight. The strengthening wire, which has previously been bent into a circle of the required diameter, is placed in position, and more plaster is added to make the ring some 1½" to 2" thick, at the same time making three rough excrescences equidistant on the ring to serve as feet, of sufficient height to keep the bowl of the dish from touching the bench when turned over. These feet or supports are shown at S in the drawing. If preferred in place of only a ring, the entire back of the dish can be covered, making it one with the bottom half of the case.

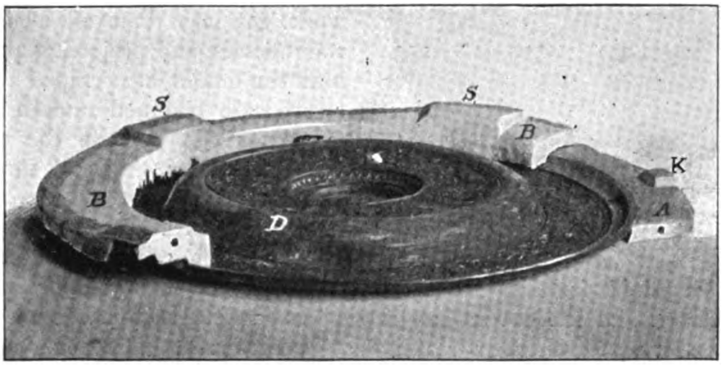


FIG. 101.—SHOWS FIRST STEPS IN MOUNTING DISH IN PLASTER OF PARIS.

When the plaster has thoroughly set, the entire thing is turned over, the clay removed, and the face of the plaster ring scraped smooth, key-ways cut clean and freely tapered, so that there shall be no fear of gripping, and the surface prepared as described in Process No. 2, page 142.

The cover shown at P (Fig. 100) has now to be made in the following way:—Modelling clay is rolled out into bands about ⅝" thick, and cut into strips as described above. These strips are taken and laid side by side over the entire face of the dish, and extending about ⅜" on to the plaster ring. The dish is shown partially covered at C (Fig. 103), with some of the strips removed for illustration. These strips as they are placed in position are made to follow as nearly as possible the general lines of the work, as what is required is that the space between the work and the cover shall be the same at every part, short of making the clay covering in any way undercut, as it is of great importance that it shall not have the slightest tendency to grip the cover—not for the sake of the clay, but for subsequent moulds. To this end it is necessary that the clay coating shall be built up with extra clay where the contour of the object being covered makes it in any way recede. And to this extent the thickness of the clay covering must vary.

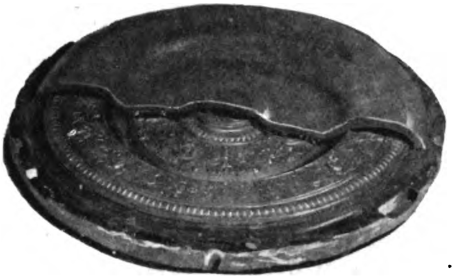


FIG. 102.—DISH AND PLASTER COVER (PARTLY BROKEN AWAY) SHOWING KEY-WAY IN PLASTER MOUNT.

The dish being entirely covered with these strips of clay as above directed, the seams between them are to be smoothed out with the fingers, kept damp by occasional squeezings of a wet sponge, and clay added where necessary to bring the entire surface smooth and regular. To make the pouring holes in the cover, two round pieces of clay, each about 2" in diameter and 1¼" high, are placed on the clay at opposite extremities of the dish. (One or more pouring holes are required, depending on the size and irregularity of the work, and they are always to be placed on high parts of the case.)

The exposed portion of the plaster ring B is freed from all clay and greased with No. 2 grease (page 140) and the clay covering well sponged with water. Plaster is mixed as directed at page 148, and a cover cast as directed at page 152. When the plaster has quite set, the cover is gently loosened by prising with a knife between it and the base, and it is then lifted from the work, the clay removed, all irregularities, roughnesses, and projecting parts liable to bind the mould, are scraped away, and the entire case trimmed smooth and regular, using for the purpose the tools shown, but the plaster ring and that portion of the cover which beds on to it must not now be touched. The pouring holes have to be cut true and well tapered inwards, and small holes bored for vents in high parts of the case, and wherever air is liable to be trapped. They can be bored with a penknife, and are made to taper inwards; and the inside of the cover being trimmed, all that now remains to finish the case is to prepare its surface as described in Process No. 2, page 142. If it is intended to be used for gutta-percha moulding, it will be better to dry it before varnishing.

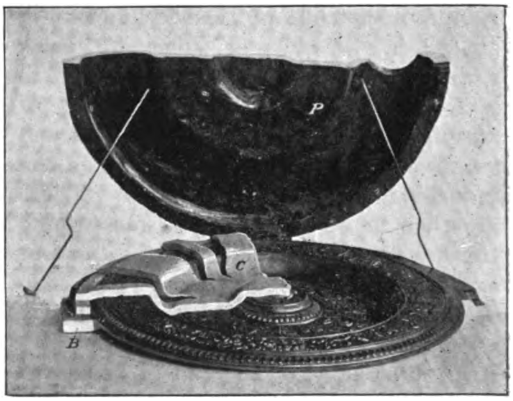


FIG. 103.—SHOWS METHOD OF MAKING SPACE BETWEEN COVER AND DISH.

The plaster ring forming the base has not of necessity to adhere to the object; all that is required is that the object, when being moulded, shall always occupy its original position on its plaster base.

EXAMPLE III.

This example represents all objects that require the mould to be in two or more pieces, the method of mounting and making cases for which does not greatly vary from the preceding one.

The objects that are classed in this example comprise all such goods as vases, lamp stands, busts, statuettes, etc., and all objects which have two or more sides to be copied.

For work of this class the first consideration is the line of division—*i.e.* the splitting up of the mould into two or more parts in the best manner to enable the separate parts to leave the work with the least possible strain on the mould, at the same time making these lines of division pass over that portion of the work where they least interfere with, or do damage to it.

The lines of separation of the mould are usually the lines of separation of the case. For work that only requires a two-part mould the line of separation is generally made to split the object into two, as nearly as possible, equal parts, but no fixed rules can be given for splitting up of work, as every object will have its own best lines of division. The considerations above are only as a guide for choosing the separation lines.

Briefly, the routine followed for obtaining moulds from work comprised in this example is to first obtain a cast of the work to be copied in plaster-of-Paris in two halves by means of the gelatine composition, these two halves making together a perfect copy of the original. From these plasters the gutta-percha composition mould is taken. If the mould will draw, the same plaster does for a number of copies; if it is undercut, and so necessitates the breaking out of the plaster, as many thin plaster casts have to be taken from the jelly as copies of the original are required.

By this method the original can be of any material, and copied without injury. For metal originals, which will draw in a two-part mould, a somewhat simpler method can be employed. This will be given after the routine outlined above, which in detail is as follows:—

The simplest example of this class of work is a plaster-of-Paris bust, which can have a straight line of division passing over the top of the head immediately behind the ears and down over the shoulders, splitting it into two nearly equal parts. It can be fitted with a case, and moulded thus. First a narrow strip of clay rolled out as described at page 157, about ⅜″ wide by ½″ thick, is placed right round the intended line of division (with a little pressure it is easily made to adhere to the work), so that the top edge of the clay band, which is about ⅜″ broad, is exactly level with that line at every part, after which it is placed face up upon a piece of sheet iron or a board, and a shelf about 2″ broad is roughly built up (with pieces of plaster and clay) to the bottom edge of the thick clay strip all round, including half of the base. Some plaster is then mixed as directed at page 148, and a level shelf built up with it on top of the loose pieces of plaster and clay, which serve as foundation, to the top level of the clay strip right round the bust, the base included. This plaster shelf is trimmed smooth and level with the clay strip, so that the top level of the combined clay and plaster shelf is on a level at every part with the intended division line of the bust. Countersunk holes are drilled in this shelf for keys. These keys are generally placed on the plaster ring at places where it is broadest, and the surface prepared as described in Process No. 2 (page 142), after which the exposed half of the bust is covered with clay, as described at page 158. Four clay keys similar to those shown in previous examples are placed in position on the plaster shelf, close against the clay-covered half of the bust. These are intended for making keys in the case for holding the gelatine tightly in position when it no longer has the support of the original.

The surface of the clay is to be painted with turpentine, and the plaster shelf with the grease composition No. 2 (page 140).

Sufficient plaster is now mixed as directed at page 148, and the first half of the case cast as directed at page 158. When the plaster has quite set, the cover is removed from the plaster shelf and the work by introducing a knife at various parts between it and the shelf and loosening it by gentle prising. All the clay is removed from it, and the inside scraped smooth, pouring and vent holes cut smooth and tapered inwards, and the keys in the side of the case cleaned and cut true, all as before described at page 158.

The surfaces of the inside of the case and the pouring holes, etc., are to be prepared as described for this class of work at page 141, and the plaster object with its flange or shelf of clay and plaster thoroughly cleaned and freed from all clay, dirt, etc. (especially must the edge of the clay touching the original be cut clean and true), and greased with composition No. 2 (page 140), in the manner described in Process No. 8 (page 145). The cover is then replaced in position on the work, securely bound up, funnel placed in position, and the jelly mould formed as described at page 147.

Note.—The original plaster bust must have had its surface prepared as described in Process No. 1 (page 141), at starting, before the clay division band was placed in position.

When the jelly has thoroughly cooled the cover is loosened from the work as before, and the jelly also loosened round the edges, but not entirely removed from the work. The cover is again replaced in its proper position, and the entire thing turned over on the iron plate, propping it steady with pieces of clay, etc. The remaining half of the work is freed from all clay and the original plaster shelf removed, exposing a shelf made up of the edge of the jelly mould and the edge of the first half of the plaster case. All ragged edges that the jelly may have are cut away, and keys cut into the edge of it at places which are likely to fall out of register. These keys are cut with a sharp knife in the shape of a long trough. The second half of the base, which has not a shelf, is provided with one as originally described, and the remaining exposed half of the work is covered with clay, the clay keys and piece of clay for pouring hole placed in position, the clay and plaster surface soaped and greased respectively, and the other half of the case cast, all as previously described for the first half. After allowing time for the plaster to set, the half of the case last cast is lifted from the work, trimmed up inside, and its surface prepared as for the previous half. All the clay is removed from the work, which is cleaned and greased as before. The exposed edge of the jelly must have its surface protected as described in Process No. 6, and greased with grease composition No. 1; other surfaces must be treated as before. The cover is then replaced in position and strongly bound up, the funnel placed in position, and the remaining half of the jelly mould poured, all as before described. When the second half of the jelly mould has thoroughly hardened, the plaster covers are separated and the projecting pieces of jelly (the runners), vents and pouring holes are cut away level to the back of the mould. The separate halves of the mould are then gently lifted from the work and replaced in their respective halves of the plaster case. The surface of this jelly mould ha then to be prepared as already described for this work. This mould can now be nothing but a perfect copy of the original in two pieces, as the second half of the jelly covered everything that was not covered by the first half, and itself butted down on the edge of the first half.

Now, if these two half moulds in their respective cases are tightly bound together, the opening will be at the base, and if a plaster cast were taken from them, as described at page 149, a perfect reproduction of the original in plaster is obtained; but if, instead of this, a cast in plaster is taken from the two halves separately (in the manner described in Example II., page 149), carrying the plaster to the extreme edges of the plaster covers, two casts are obtained, each carrying a perfect half of the original with its plaster shelf and keys necessary for making it tight, with its proper half of the case. If, now, the jellies are removed, and they are tied up with their respective half cases (after having their surfaces prepared as described in Process I., page 141), as many gutta-percha moulds can be taken from them as are required, which will serve either for types in two halves or in one piece by binding them together. If it is a subject that will not draw, the plasters must be sacrificed for each mould. When this is the case, as many plasters are taken as copies of the original are required, and they are cast as thin as is consistent with safe handling.

The first plaster cast taken of the back half of the work is usually put on one side, and kept with the original as a means of obtaining a fresh jelly mould whenever required without the trouble of re-making the case. Thus, the plaster half of the back (after having its surface properly prepared) is bound up in its proper half of the case, and a jelly poured with the proper precautions. When the jelly is quite hard, the cover of the case is lifted off and the jelly mould gently lifted from the work and replaced in position in its case. The original is then placed in position in the mould and made to bed truly in the place formerly occupied by the half plaster cast. The other half of the case is put in place and the mould bound up. The remaining half of the jellies can then be poured with, of course, all the precautions previously described. Thus as many jelly moulds can be taken as desired, every one of them as good as the first. If it is not possible to keep the original, a plaster copy of it must be taken from the first jelly at the same time as the first half. This is preserved, and serves as the original.

For work which is likely to be much used it will be well to obtain a type of the back half complete with the shelf and keys, which will last for all time, without danger of injury.

The above method, although illustrated by the simplest work of its kind, is suitable for the most complicated and delicate bronzes. The division lines have no necessity to be straight; they can be made to follow any lines most suitable to the work in hand.

METALLISATION OF GUTTA-PERCHA COMPOSITION MOULDS.

The materials necessary are finest divided copper-bronze powder, specially prepared for electrotyping purposes, containing nothing but copper, and free from grease.

A weak silver solution prepared by dissolving ½ oz. of silver nitrate in 3½ pints of distilled water, ½ pint of methylated spirit, and 20 to 30 drops of nitric acid.

Badger-hair brushes of various sizes should be used.

A good conductive coat can be given to gutta-percha composition moulds in the following manner:—The face of the mould is to be repeatedly brushed over in every part with a brush kept plentifully charged with the copper-bronze powder, the velvety surface of the composition readily taking the powder. But it is not sufficient to simply bronze the surface of the mould; the copper powder should be made to penetrate somewhat into the pores of the composition by keeping an abundance of powder under the brush, and by a continuous and fairly vigorous brushing of every portion of the mould, holding the brush upright and moving it rapidly in every direction in small circular strokes. When this is finished the mould is stood on end and freed from the excess of bronze powder. It is then brought under the tap and a fairly powerful jet of water is played all over it, especially into the crevices and hollows of the work, to flood away all traces of loose powder from every part of the mould, after which it is placed, face up, in a shallow earthenware or wood tray, and the silver solution, above given, applied by pouring it in a continuous small stream directly on to the face of the mould from a jug held a foot or so above it, so that the solution strikes the mould with some force, and is so driven into the intricacies of the work. The entire face of the mould has to be gone over in this way, and the process must be persisted in until every portion of the bronzed surface has turned a dull greyish colour. Should there be any spots which still retain their copper colour (caused by imprisoned air), they are given a gentle blowing with hand bellows, whilst the mould is still immersed in the silver solution. This operation having been successfully performed the work is removed from the silver, allowed to drain, and again taken under the tap; this time to be well rinsed with a gentle stream of water to free it from all traces of the silver solution. It is then banged on its edge on the bench to expel the water held in cavities, etc., of the work, and is finally stood on end against a wall to drain and dry.

OBSERVATIONS WITH REGARD TO THE ABOVE METHOD OF METALLISATION.

The first washing of the mould is best performed under a tap which is provided with a length of half-inch or so of soft rubber tube, which can be pinched at the end to make a jet of water of the stiffness and size desired. In the second washing the full opening is used, and the tap only turned on sufficiently to allow a full stream of water to flow without hissing, as no force is allowable at this stage.

The tray for the silver reduction can be of earthenware or a shallow wooden box having a bottom sloping to one corner, in which is a hole about 1 in. in diameter, closable with a rubber bung. This enables the silver solution to be rapidly returned to the jug without lifting away the mould that is under operation. The wooden tray can be made watertight by giving three or four coatings of a cement made by mixing dry white lead with good copal varnish until it is a stiffish cream. One coating must be allowed to dry before the application of another.

The bronzing can be performed over a shallow wood or cardboard box lined with glazed paper. The bronze powder being very injurious to inhale, it is advisable, whilst working with it, to have the nostrils plugged with cotton wool and to breathe through it, keeping the mouth closed. For constant work with this material a large box should be provided, having an easily movable glass cover, and in its sides two armholes provided with short sleeves of lining, throttled with an elastic band.

Under the action of the silver solution the copper surface should turn grey very slowly and uniformly ; it is to be stopped before the deposit becomes too dark. If pushed too far, or the silver solution used too strong, the reduction is coarse, with little adherence to the mould.

The action that takes place when the silver solution is poured upon the bronzed surface is that the silver in solution is reduced by the metallic copper and thrown down on the surface of the mould, and an equivalent amount of the copper replaces the silver in the solution as copper nitrate, so that all that is necessary for the above purpose is a slightly acid solution of silver nitrate with just sufficient silver dissolved in it to effect the reduction slowly; the methylated spirit is added to overcome the slight greasiness of the copper-bronzed surface. If the solution acts too rapidly it must be diluted with water until it works at the desired rate. The percentage of free nitric acid is also to be controlled by the condition of the deposit, too much acid making the deposit black and powdery; not enough, the reduction is too slow and the deposit has a violet shade, which is not so good a conductor as when the deposit is a darkish dull grey when wet, turning to a French grey with a fairly bright surface on drying.

A mould, simply copper-bronzed, is sufficiently conductive to receive a deposit, but with the silvered surface the spread of the deposit is more rapid, as the copper surface, obtained by the bronze powder, is not continuous, but consists of countless small particles of copper, more or less in touch with one another, its surface being always slightly greasy, and in such a finely divided state the free acid in the bath has a dissolving action upon. it. The bath has no action whatever on the silver, and when thrown down as above directed, it is a homogeneous and continuous covering which is quite chemically clean.

A mould prepared as above directed is not to be immersed in the bath until quite dry. If immersed damp, the spread of the deposit is not so rapid; moreover, in drying, the coating of silver gets smoother and more compact, which condition subsequent wettings do not seem to disturb.

PREPARATION OF METAL SURFACES EMPLOYED AS MOULDS.

When depositing a metal upon a mould or object, also of metal, from which the deposit has to be separated, it is necessary that the surface of the metal that is to be deposited upon should be prepared in some manner to prevent an inseparable adhesion of the metal deposited. The flatter the surface deposited upon, the less danger of sticking; the greater the inequalities of the surface deposited upon, the greater must be the care with which it is prepared, as only a small area of adhesion may be quite sufficient to ruin both the type and its mould. For copper strip moulds (*i.e.* thin copper shells which are to be torn from the type) the danger is not so great as for solid copper moulds which have to be bodily separated from the copy.

COPPER TYPES FROM COPPER MOULDS.

Copper moulds or clichés can be prepared as follows :—They are to be cleaned and given a thin deposit of silver, ten minutes' immersion in the bath being quite sufficient, on removal from which they are swilled in water, scratch-brushed, and immersed in or painted with a warm solution of potassium iodide (a ¼ oz. of potassium iodide in every 20 oz. of methylated spirit) until a green coating (silver iodide) is obtained on every part. After being rinsed they are to be exposed for an hour or so to the light, after which they are ready for immersion in the copper bath.

SILVER TYPES FROM COPPER MOULDS.

A copper mould for depositing silver into is prepared as follows:—The mould is to be thoroughly cleaned as for plating (see page 115), but dispensing with the quick. After the final rinsing it is connected to the negative pole of a dynamo or battery, and immersed face up in a hot solution of cyanide and arsenic. Then a piece of platinum or aluminium foil is attached to the positive pole and "walked" over the face of the work (as described for the iodine process) until it is covered with a uniform thin darkish-grey deposit of arsenic, fairly bright. After a rinsing, it is ready for immersion in the bath.

The arsenic solution is prepared by mixing 8 oz. of sodium arsenate in 1 gallon of water containing 4 oz. of cyanide. This is boiled for half an hour, then filtered, and used at a temperature of 50° to 60° C.

METALLISATION OF ARTISTS' WAX ORIGINALS.

When an artist's wax original is to be reproduced by means of the waste or strip copper-mould process, it has to be metallised in precisely the same manner as described for the gutta-percha composition moulds (page 161), only using a soft camel-hair brush in place of the one there recommended. It is necessary to use as little pressure for the bronzing as is consistent with the sufficient adherence of the bronze powder. The brush must always freely slip over the surface of the wax; if there is a suggestion of drag (caused by insufficiency of powder under the brush) the work is being spoilt. The nature of the material enables the bronzing to be effected with very little pressure, so that with ordinary care it can be done without any danger of loss of detail. The wax original should be kept in a cold place for some time before being bronzed.

EQUIPMENT OF GUTTA-PERCHA COMPOSITION MOULDS.

After the operation of silvering previously described, the mould has to have two or more copper-wire loops embedded into its edge for suspension. Thus, two short lengths of copper wire of a thickness commensurate with the weight to be supported (12 to 16 B.W.G. are useful sizes) are to be bent to a **U** shape. Holding one of these with the pliers, its bent ends are to be heated over a Bunsen flame until dull red. It is then immediately inserted into the edge of the mould (which is on its back on the bench) until its bent ends are immersed in the mould some ¾ in. to 1 in. In inserting these loops care must be taken not to penetrate the metallised surface. Two or more of these loops are placed equidistant round the mould to enable the position of the mould in the bath to be reversed, so that the thickness of the deposit can be equalised.

When the gutta-percha round the loops has hardened, it is to be metallised with a small brush charged with bronze powder so as to bring the metallised face of the mould in contact with the copper suspension loops, and with a cloth pad moistened with methylated spirit all the metallisation is removed from the edge of the mould, and for some ¼ in. on to the face right round, excepting the bands joining the copper loops, so as to minimise wasteful deposit as much as possible.

The slinging hook is made of wire or strip, and of such a length that the junction with the loop on the mould is immersed in the solution when in position on the suspending rod. These hooks are made with double ends to prevent swinging about. The stoutness will, of course, depend on the weight to be supported. Nos. 16, 14, 12, B.W.G. will, in the ordinary way, be serviceable for moulds up to 36 in. in diameter. A better slinging hook is made of strip copper 1 in. broad. It makes a better connection electrically and holds the mould more rigidly in position. In both the wire and strip slinging hooks, the top hook has to be bent so that it springs a little on to the suspending rod.

Finally, the specific gravity of the gutta-percha composition being less than that of water, it is necessary to weight the moulds made of this material to sink them in the copper bath. Weights for this purpose are conveniently made by casting a rod of lead and cutting varying lengths from it, depending on the weight required, and through the centre of each of these pieces drilling a hole large enough to pass a strip of celluloid about $\frac{1}{4}$ in. wide by $\frac{3}{16}$ in. thick. One end of this is filed to a tapered point, and is then heated in boiling water, when it can easily be bent into a hook. It is then passed through the hole in the lead, and the other end bent up to prevent it dropping through. A $\frac{3}{16}$ in. celluloid rod will do as well as the strip, or vulcanite treated in the same manner as the celluloid; but this latter is very brittle, and breaks up if the weights are knocked about. If neither of the above are convenient, wire can be used with a piece of stout rubber tube over the hook to prevent contact with the suspending loop.

For the first twelve hours of the immersion of a mould in the bath a current density of from 10 to 12 amperes per square foot can be employed; after that, for backing up, 15 to 25 amperes can be employed for the same surface. If the objects are in movement in the solution, this current density can be considerably increased.

The slinging hooks should from time to time be changed from one suspension loop to another, so that all portions of the mould have their turn at the bottom so as to equalise the thickness of the deposited metal whether in movement during the depositing or not; that portion of the mould which is lowest in the solution obtains the most deposit, as the lower strata of the solution become denser and contain more copper than the upper layers.

The anode surface is to be about equal to the surface of the moulds being covered.

The distance of the moulds from the dissolving copper sheet is to be not less than 4 in.; if the mould has a great inequality of surface the distance apart should be greater. If anodes other than electrolytic copper are employed (that are not too heavy to handle freely), it is well to remove them from the bath night and morning, and to brush the black mud from them, as it keeps the solution freer from dirt, etc.

Moulds that are being typed in the round will have their anodes suspended inside; they are usually rods or strips of copper depending on the size of the openings of the mould. For the mould of a vase a stout copper rod is suspended so that it passes through the mould without touching. On to this copper rod are slipped two short lengths of soft rubber tubing, fitting the rod tightly; these are placed just where the anode passes through the narrow parts of the mould, so as to avoid short-circuiting the current through the anode touching the mould.

SECTION IV.

THE MAGNETIC CIRCUIT AND INDUCTION.

CHAPTER I.—GENERAL MAGNETIC EFFECTS.

THE LODESTONE—STEEL MAGNETS — POLARITY—TERRESTRIAL MAGNETISM—ELECTRO-MAGNETISM.

THE LODESTONE.

At the ancient city of Magnesia, in Asia Minor, are found considerable quantities of a mineral which has the peculiar property of attracting iron, and of adhering to it with considerable force. This mineral was well known to the Greeks, who were familiar with its most striking properties. The Greeks named the mineral "magnes," from the city of its origin, and the properties it possesses are hence called magnetic. The mineral is an iron ore giving, on analysis, the composition Fe_3O_4. It probably consists of protoxide of iron FeO (ferrous oxide) and peroxide, Fe_2O_3 (ferric oxide), being possibly a kind of solution of one in the other. It is a lustrous dark grey substance, forming regular octohedral crystals of specific gravity 4·25. This mineral is found in many other places, viz. in Germany, Sweden, Spain, and China; but it does not always exhibit the property of attracting or adhering to iron when found, though the property may be imparted to it. It is hence known as magnetic ore, whether found already possessing the attractive property or not. It is also known as black oxide of iron, and may be prepared in a small way by plunging red hot iron into water, when a black scale of magnetic oxide will be formed. It is better prepared by passing steam over iron turnings which have been placed in a tube and are heated to a red heat.

The Greeks do not appear to have been familiar with an important property of the mineral, viz. the tendency of a piece of it to set itself so that its parts always occupy the same relative geographical position. This would only be apparent if it were suspended so as to be free to turn in a horizontal plane. For example, if a spot of black and a spot of white paint be put on two opposite parts of a specimen and the specimen be freely suspended, a line joining the two spots will always have the same geographical direction when the specimen comes to rest. It might happen that the black spot was always due east of the white. This property does appear, however, to have been known to the Norwegians about the end of the eleventh century, and the stone was consequently called the "leidarstein" or guiding stone. The English word corresponding to and having the same meaning as this is "lodestone," and the native magnetised mineral is still known by this name.

A specimen of the stone does not exhibit equally at all parts its property of attracting iron objects, but is generally found to possess two points or regions of greatest activity in this respect.

STEEL MAGNETS.

One of the most striking properties of the lodestone is that in virtue of which it can impart its own properties to a bar of hard steel. If a bar of steel be stroked along its length with one of those parts of a lodestone which show the strongest magnetic effects, the steel bar itself will thereafter behave as a lodestone. Care must be taken, if the bar is stroked more than once, to stroke the bar in one direction only, beginning the stroke at one extreme end of the steel bar and continuing it uniformly to the other extreme. The steel bar is then known as an artificial magnet, or, more commonly, as a "permanent magnet," since it retains its magnetic properties indefinitely if carefully handled. Bars of soft iron or mild steel may be similarly treated, but they do not exhibit the above magnetic properties so strongly, nor do they retain their magnetism so well as hard steel. A smart jar or blow is usually sufficient to remove all signs of their having been magnetised. A good steel bar, on the contrary, retains its "memory," if we may so call it, of having been touched by the lodestone well, and exhibits the lodestone properties very perfectly. Either end of it will attract and pick up small iron objects, such as nails, nibs, etc.; and, if suspended horizontally, and free to turn, it will oscillate to and fro about its suspension, until it finally comes to rest, with its length lying practically north and south. Since it is difficult to find for, so heavy an object, a suspension which is free from twist, the latter property of the bar magnet may be better observed by placing it on a large cork in a basin of water. It will be found that not only does the bar-magnet, when left to itself, always take up a position with its length running north and south, but that the *same* end always points south, and the other end, therefore, always north. The two ends are hence commonly known as the "south end" and "north end" respectively, but many text-books refer to them as the "north seeking" or "marked" end, and "south seeking" or "unmarked" end, for reasons which will appear later on. In this work, however, the end that points north will be called north, and the end which points south will be called south, since this is simpler and confusion is not likely to arise.

In order to obtain powerful magnetic effects starting from a lodestone, it was usual to prepare a number of small steel magnets and to bind them together in a bundle. Having obtained such a "magazine" a magnet much stronger than the individual members of the magazine could be made by stroking a larger bar of hard steel with one end of the magazine, care being taken, as before, always to stroke in one direction, and not to rub to and fro. For a long time it was supposed that the harder the steel, the better it retained its magnetism, no matter what the shape or dimensions of the bar. If, however, a bar of steel of some thickness is hardened glass-hard, it will be found that the glass-hard portion is in reality a sort of crust or envelope, the innermost portions of the steel being of a softer temper. This has the result that a thick bar does not make so strong a magnet as might be expected, and in order, therefore, to produce very strong permanent magnets, the best plan is to build them up of thin strips of steel not exceeding about $\frac{1}{4}$ in. in thickness, preferably not more than $\frac{1}{8}$ in. These strips, each of which is of the shape which it is desired to give the magnet, are then clamped or fastened together. The best fastening is obtained by clamping all the strips together in their proper positions before they are hardened, and drilling two or more holes right through them in that position. They may be then unclamped, hardened and magnetised separately and reassembled; brass bolts or screws may be then passed through the holes, thus firmly clamping together the strips or "laminæ." Such a magnet is usually called a compound permanent magnet, or a laminated permanent magnet. The ends are usually provided with soft iron shoes of various shapes, called pole-pieces.

POLARITY.

So far, in connection with the effect on iron or steel, we have spoken only of the *attractive* property of the lodestone or permanent magnet. Forces of *repulsion* may, however, be equally exhibited. If, for example, two bars of steel be both converted into permanent magnets by being stroked with the lodestone, or with a steel magnet, and the end which points north be marked N on each magnet, it will be found, if one be floated on a cork, that the N-end of the one held in the hand will repel the N-end of the floating one, and can be made to chase it all round the basin. Similarly, repulsion takes place between the two S-ends, while attraction occurs between a S-end and a N-end. If the magnet that is held in the hand be placed alongside the floating one so that the two N-ends and the two S-ends are close together, the floating one will be driven away from the other broadside on. The regions of greatest activity of the lodestone, already referred to, exhibit similar effects and correspond to the ends of the bar magnet. Owing to the irregular shape of most lodestones one cannot generally speak of their "ends." It might have been inferred from the tendency of a magnet to point N and S, that the two ends of a magnet exhibit different and apparently opposite qualities; the above experiments fully confirm this. To account for this the earlier theories of magnetism regarded the effects as being due to two subtle fluids, one of which was to be found on the N pole of a magnet and the other on the S pole. The fluids had to be conceived as possessing no weight, or as being what was called "imponderable," and as occupying no space. It was, no doubt, to these views of the phenomena of magnetism that the two-fluid theory of electricity owed its origin. So long as the study of electricity was confined to the effects and phenomena of what is called static electricity, that is, of charges of electricity as distinct from currents, the two sciences of magnetism and electricity advanced pretty much hand in hand. When, however, further discoveries directed men's attention more particularly to the effects of electric currents, the study of magnetism fell behind, and great progress was made in electrical knowledge, new and better theories of electricity being constantly advanced. Hence, as we shall shortly see, magnetic theory, which at one time seemed to mould electric theory, ultimately came so much under the influence of electrical ideas as to be very largely modelled on the same lines as those which govern the theory of electricity.

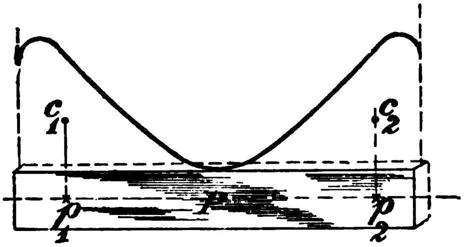


FIG. 104.—DIAGRAM ILLUSTRATING MAGNETIC FORCES DUE TO A PERMANENT MAGNET.

The ends of the magnet are commonly referred to as its poles, but there are two points a short distance from each end which are properly speaking the true poles of the magnet. These poles are imaginary points at which all the magnetism of the magnet may be supposed to be collected. To make this clear, the following experiment may be referred to. If the magnetism of the magnet be tested or explored by means of a very small iron ball, and the force which is necessary to pull the iron ball from the magnet be taken as a measure of the strength of the magnetism*, it will be found that the magnetism is strongest at or near each end, but that it gradually diminishes in strength from each end to a region about the middle of its length, where the strength is zero. The diagram, Fig. 104, represents graphically these facts, the height of the curve at every point along the length of the magnet indicating at that point the strength of the magnetism measured in the manner described.

Next, if the magnet be pivoted at P, and placed where it can be acted upon by other magnets, or by the earth's magnetism, the total "torque," or twist, tending to swing it round into its position of rest may be regarded as being made up of a number of little twists. Each of these may be represented by the height of the curve (Fig. 104) at any point along the magnet multiplied by the distance of the point from the pivot. If now we take every possible point and multiply these two quantities together at each point, we get the total torque by adding all the so-obtained products together. We could get the same result if all the magnetism of the magnet could be collected at two certain points equidistant from the pivot, half the magnetism at each point, instead of being distributed in varying degree all along the length. The position of these points is given by the distance from the pivot, measured along the magnet, of the centres of the triangular areas under the curves.

If, then, the two points c_1, c_2 are the centres of the two areas, the two points p_1 p_2 give the positions of the so-called true poles. In physics the length of the magnet proper is considered to be the distance between these two points p_1 and p_2, and the steel is regarded merely as a fortuitous envelope to the magnetism, the dimensions of the steel being unimporant except so far as the moment of inertia of the bar is affected by them. The strength of one true pole multiplied by its distance from the other gives what is called the "magnetic moment" of a magnet. This quantity is very important in magnetics, as it represents the power of the magnet to control the position of a pivoted compass needle, or the degree of its own tendency to be controlled by the earth.

The units, in terms of which magnetism is measured, are given in the section on Units and Testing.

An imaginary straight line joining the poles of a magnet is called its magnetic axis.

TERRESTRIAL MAGNETISM

The reason why a suspended lodestone or magnet always comes to rest in one definite position is that the earth behaves as though it were itself a huge magnet having two magnetic poles not very far from the two ordinary geographic poles.

In view of what has been said on p. 168 regarding the mutual repulsion of similar, and the mutual attraction of dissimilar poles, it is clear that the magnetic polarity at the "Earth's north magnetic pole," must be *opposite* in character to that at the north end of a compass needle, and *similar* to that at the end which points south. Hence if we call that kind of polarity "north" which points north because it is attracted by the northern part of the earth, the *magnetic* polarity of the earth in the northern geographic region must be called "south." It was in order to avoid confusion arising from this, that the practice of calling the poles of a needle "north-seeking," and "south-seeking," or "marked," and "unmarked," respectively, arose. In technical work, at least, it is now the universal custom to call that kind of magnetic polarity "north," which the earth has at its southern geographic region, or which in a compass needle will point north. In such terms then we may rightly say that the earth's "north" magnetic pole is in the south geographic, or antarctic, region. The study of the magnetic properties of the earth is extremely interesting, but is of little value to the electrical engineer. The engineer who has some accurate research work to do may need to know or to measure the strength of the earth's magnetic field in his laboratory, and a method of determining it is given in Section V. A detailed knowledge, however, of the daily and yearly variations of that field are of value rather to the meteorologist than to the engineer, however interested the latter may be in them from a scientific standpoint. Not much more need be said, therefore, in a work of this scope than that the earth's northern magnetic pole is situated somewhere in Boothia Felix, that its position varies, and that therefore the indications of the compass vary from time to time. A knowledge of these variations is, of course, of very great importance to navigators.

---

* The presence of the ball disturbs the normal distribution of magnetism, and the method is therefore inaccurate. It is, however, very instructive, and the results are of the right order.

The present position is such that a compass needle in England points about 16 degrees west of true north. At any place due south of the northern magnetic pole, the compass points true north, of course. A magnet which is perfectly free to turn in a vertical plane as well as in a horizontal one will not only point a little west of north in England, but will tilt with its north end pointing down towards the ground. The angle which the magnetic axis of the needle makes with the horizontal is called the angle of dip, and in London is now about 67°. The true direction here of the earth's directive action on the needle is thus along a line sloping down towards the earth, like the direction of raindrops when a strong wind is blowing from the S.S.E. Mention is made of this here because in certain galvanometer work and in some methods of iron testing the "horizontal component" and the "vertical component" of the earth's directive force are referred to and utilised. Methods of measurement of these are given in the section on Testing. The earth's action on a needle is purely directive and not translational. This is seen when a magnet is floated on a cork; it is swung round but is not drawn bodily by the earth's magnetism in any one direction. It is easy to show that the force of gravity is distinct from that of magnetism by weighing a piece of hard steel before and after magnetisation. Magnetisation does not alter the weight.

ELECTRO-MAGNETISM.

The magnetic effects of an electric current have already been referred to on page 7. They are readily obtained of great strength, and are hence of far more value to the engineer than the magnetism of steel magnets; whilst that of the lodestone is useless.

It has already been pointed out (page 7) that a current flowing in a conductor is capable of affecting a compass needle. This effect varies with the strength and with the direction of the current. If the current be reversed, its action on a compass needle is also reversed, and the effect also increases or decreases with an increase or decrease of the current strength.

The nature of these magnetic effects may be exemplified as follows.

In Fig. 105 (*a*) *w* represents a wire lying N and S, beneath which is a compass needle *c* at rest, *i.e.* pointing N and S. By the side of the wire and to the east of it is a second magnetised needle *d* mounted on a horizontal axis, balanced so as to lie horizontal, but otherwise free to turn in a plane parallel to the length of the wire. If now a current be sent through the wire in the direction of the arrow the two needles will move to some such positions as are shown in dotted lines, or if the current be strong enough, they will take up the positions indicated in Fig. 105 (*b*). If the magnet needles

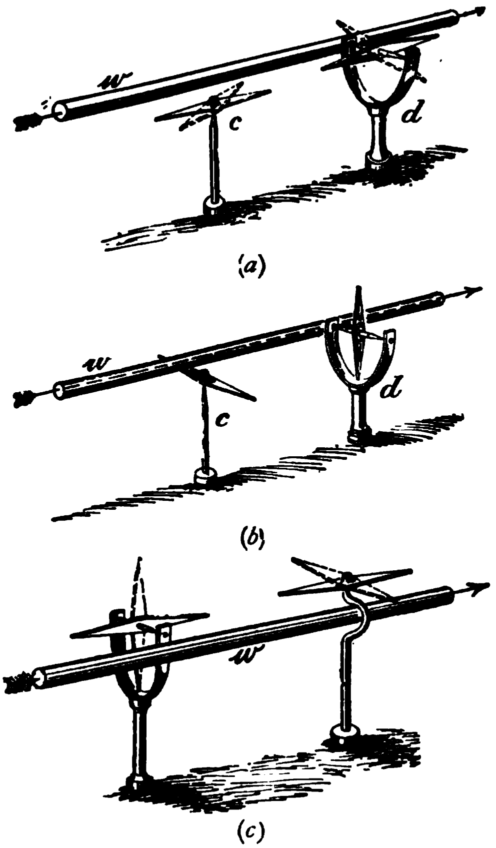


FIG. 105 (*a*, *b*, *c*).—ILLUSTRATING THE DIRECTIONS OF MAGNETIC FORCES DUE TO CURRENT IN *STRAIGHT WIRE*.

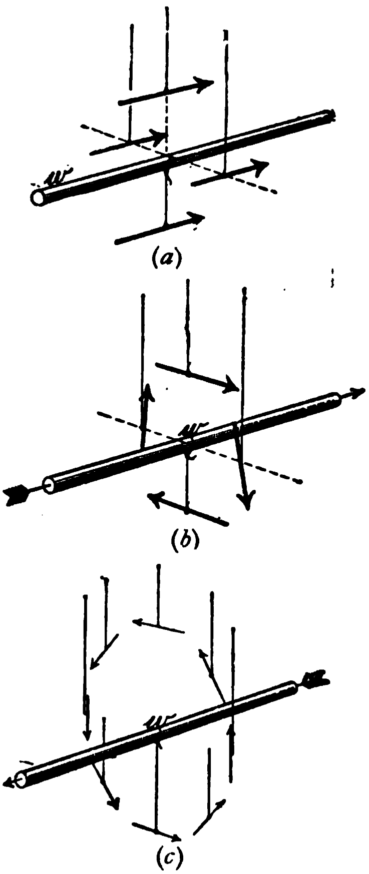


FIG. 106.—ACTION OF A CURRENT ON COMPASS NEEDLES.

were in the positions shown in Fig. 105*c* (viz. *above* and to the *west*) the tendency to move would be as shown there, and if the current were reversed in either case, the action on the magnets would be reversed. Finally, if four little magnets were suspended as at (*a*) in Fig. 106, free to turn in any direction, they would take up the positions (*b*) if a strong current were sent through the wire in the direction of the arrow. If the direction of the current were reversed the position taken by the magnets would be as at (*c*). In this last sketch four additional magnets have been added in positions intermediate to those occupied by the first four, and it will there be seen that the apparent tendency is for the magnets to set themselves in a circle with the wire passing through the centre, at right angles to the plane of the circle. In point of fact this is the tendency, without reference to geographic direction. If the wire could be surrounded by an innumerable number of extremely small magnets, all at the same distance from the wire, these would set themselves into a true circle. Nor is it difficult to make this investigation experimentally. Let the wire be brought up through a hole in a horizontal piece of smooth wood, or preferably through a piece of glass, as at Fig. 107, where *w* is the wire seen above the glass and *w*, the same wire beneath the glass and seen through it. Now let the glass be uniformly sprinkled with iron filings. Each little filing behaves like a very small magnet, and is subject to the directive

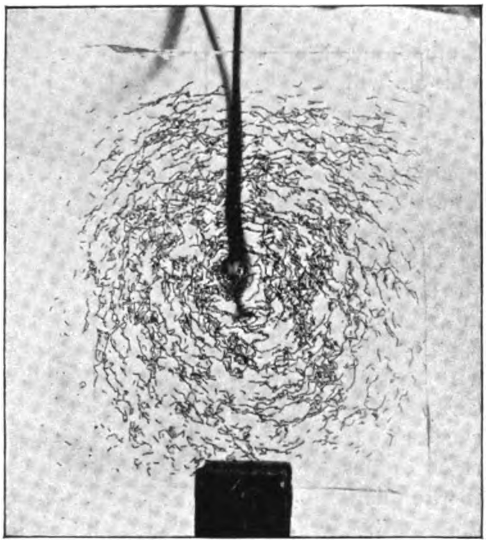


FIG. 107.—IRON FILINGS IN MAGNETIC FIELD DUE TO VERTICAL CURRENT.

action of the current in the wire, so that when a fairly strong current is sent through the wire, the filings at once take up positions forming concentric rings round the wire. The formation will not be perfectly regular, but will be fairly so, and may be greatly assisted by gently tapping the glass to eliminate the friction between the filings and the glass.

If the current be stopped the filings remain as they were when it was flowing, since the action of the earth, tending to make them point north and south, is too weak to move them on the glass. Even if the glass be tapped only a confused figure will result, since the filings are not ordinarily magnets, but become magnetised by the current in the wire. When this stops they retain some little of their acquired magnetism, but the jar at once deprives them of nearly all, and they also react on one another magnetically in such a way as to entirely mask any effect due to the earth.

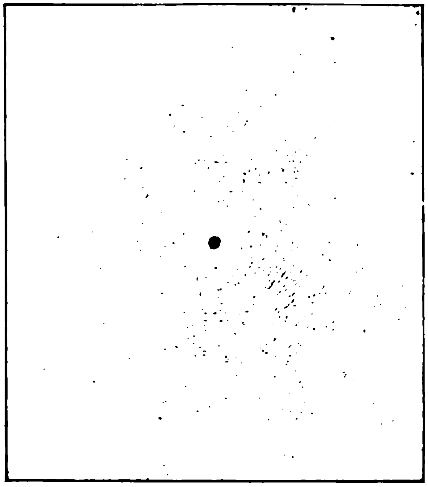


FIG. 108.—FILINGS SHOWING MAGNETIC FIELD ROUND A WIRE CARRYING CURRENT.

Fig. 107 is photographed from a plate used by the author having a wire 0·064 of an inch in diameter and a current of about 100 amperes. The major part of the wire being vertical is end on, and cannot be well distinguished. The two horizontal portions were at some distance from the glass plate, and are therefore blurred.

By repeating the experiment with a thicker wire (dia. = 0·15 in.) and the same current, Fig. 108 was obtained, the filings being on card instead of glass, and being finer than those in Fig. 107. This leads us to a consideration of two interesting matters. One is the question as to where precisely the magnetic force originates, and the other is whether or no there is any magnetic force at work inside the wire itself. Let us repeat our experiment with a rod and with a tube, using first one and then the other, and employing the same current each time. The results are given in Figs. 109 and 110. From these two results one thing is at once apparent, and that is, that the external effect is the same in both cases. From the heterogeneous arrangement of the filings inside the tube it would appear that there are no forces there, which in one sense is—and in another is not—the fact.

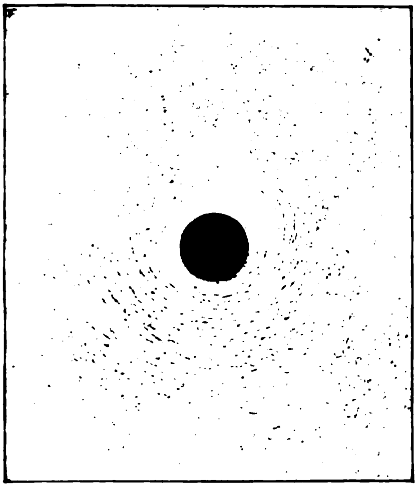


FIG. 109.—FILINGS SHOWING MAGNETIC FIELD ROUND A ROD CARRYING CURRENT.

Rod 1 in. in dia.: current 150 amperes.

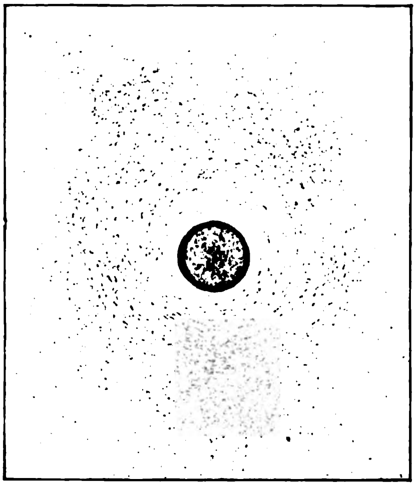


FIG. 110.—FILINGS ROUND AND INSIDE A TUBE CARRYING CURRENT.

Tube 1 in. external dia.; current 150 amperes.

The tube may fairly be considered to be an agglomeration of a number of wires of shape) in section, placed side by side.

If we suppose the current to distribute itself fairly through the section of the tube, we may say that each of these supposed wires gets the same proportion of the total current. Each by itself, therefore, would show precisely the same filings picture, and would exert identical forces. When they are all assembled in place, side by side, the interior of the tube so formed is a battlefield of conflicting magnetic forces, which, thus combined, can effect nothing. They do not exactly annihilate one another, though the effect is what it would be if they did; they are all still there, but effectually neutralise one another's action.

If we say that these forces neutralise one another's action we ought to justify the statement, at least to some extent, by showing how this may be. We have already gained the information that the magnetic forces exerted by a current may be reversed in direction by the reversal of the current as, for example, in Fig. 106, on page 171; but it will be well to examine the question a little more closely at this point. In Fig. 111 is shown a horizontal plate of glass on which have been placed a large number of compass needles of the charm type, that is, pivoted between glass plates. Through the centre of the glass plate a hole has been drilled, and through this a vertical wire is led. The vertical portion is of some length, and at the top and bottom of this vertical length the wire is bent in a horizontal direction at w and w_1 respectively. The charms and the wire have been photographed in this position and, owing to the fact that the wire is vertical where it passes through the plate, the upper and lower portions do not come properly into the field of view, but are somewhat indistinct. It will be seen that in Fig. 111 the needles are pointing haphazard in all manner of directions, although the greater number of them appear to be pointing to the bottom edge of the picture, this in fact being the northerly direction at

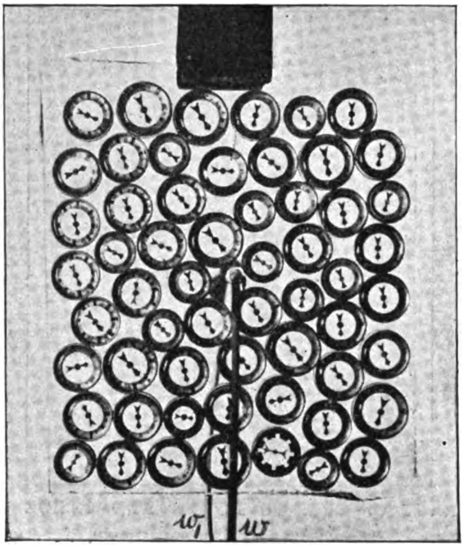


FIG. 111.—"CHARM" COMPASS NEEDLES ARRANGED ROUND VERTICAL WIRE. NO CURRENT IN WIRE.

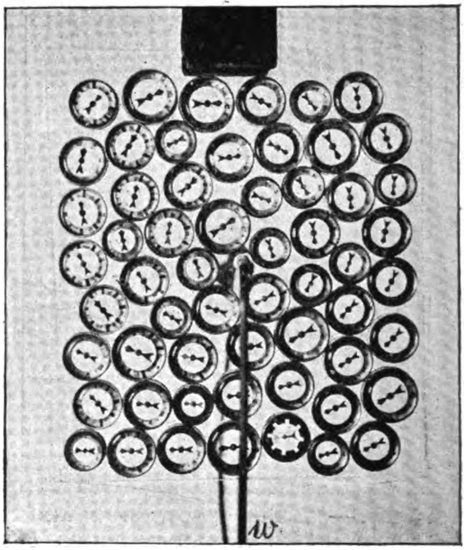


FIG. 112.—EFFECT ON COMPASS NEEDLES, DUE TO CURRENT FLOWING *DOWN* VERTICAL WIRE.

the time the photograph was taken. The needles having been allowed to come to rest, as shown in Fig. 111, a current was then switched on, with the result that they took up the position shown in Fig. 112. A glance at this figure at once recalls Fig. 107, since the needles are clearly tending to set themselves in concentric circles in exactly the same way as did the filings there. The needles, however, give this additional information, namely: that they are all pointing in a set direction, and that if one passes a pencil from tail to tip of one and then into the next adjacent needle in the same direction, the pencil point will travel round the wire in a clockwise, or "right hand," direction. Now if there had been by the side of this wire, and just to the right of it, a second also carrying a current in the same direction as the first, there would have been in the space between them a tendency due to the first to make the needles point to the lower edge of the figure, and a tendency due to the second to make the needles point toward the top edge. Hence we are justified in saying that there is conflict at this region between the forces due to the one wire and those due to the other. If we carry this argument further and arrange a number of wires round the circumference of a circle, to represent the tube shown in Fig. 110, a little reflection will show that we are justified in saying that the enclosed circle becomes the region of conflicting forces whose total effect is *nil.*

In Fig. 113 we have the filing arrangement that is obtained when the current is sent through two flat strips. In this case the two strips were about 2½ in. wide and $\frac{1}{16}$ in. thick, and both carried current down through the plane of the paper, and in Fig. 114 two strips are shown some little distance apart, one carrying current down and the other bringing it up. In the latter case the strips were of different material, in order to show the effect on the field of the material of the conductor carrying the current. The upper strip

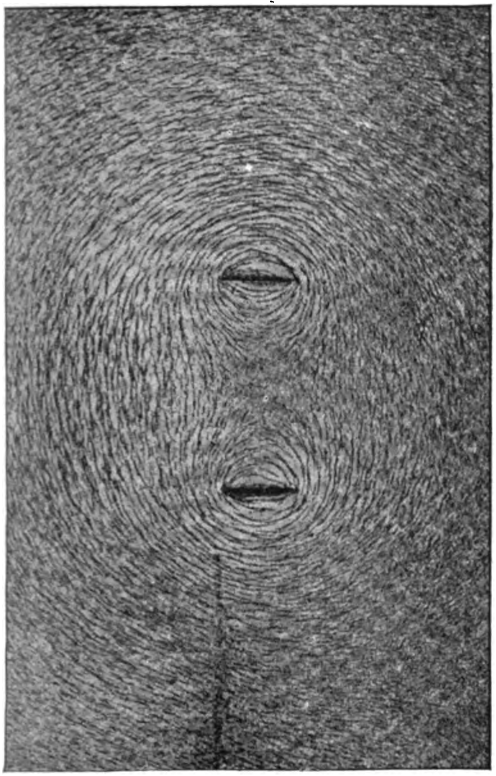


FIG. 113.—FIELD DUE TO TWO STRIPS BOTH CARRYING CURRENT IN THE SAME DIRECTION.

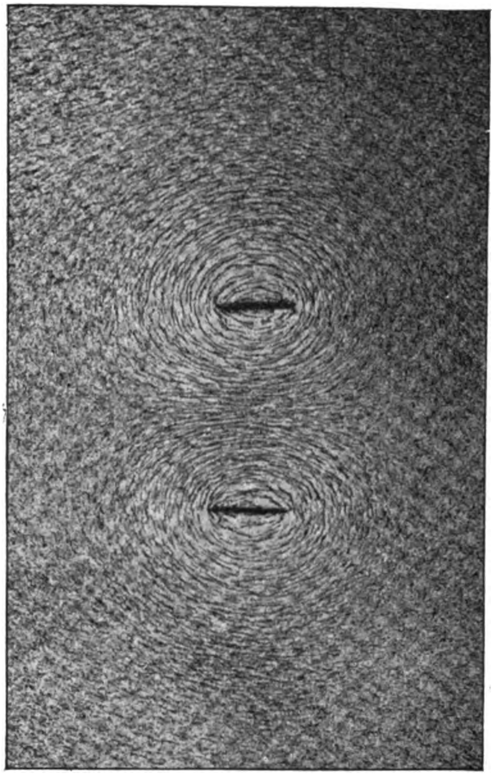


FIG. 114.—FIELD DUE TO TWO STRIPS CARRYING CURRENT IN OPPOSITE DIRECTIONS.

in this case was iron and the lower one brass, and a current of 250 amperes was sent through the two in series. An inspection of the arrangement of the filings fails to show any marked difference that can be attributed to the material of the conductor. In point of fact there should be no difference, and the figure should be symmetrical about the centre line passing between the two conductors. The only difference occasioned by the use of a magnetic or non-magnetic material for the conductor arises within the conductor itself, and cannot be shown experimentally except by methods which depend on far more advanced treatment than that of mere filing pictures.

Other phenomena observable with straight wires are the mutual attraction of two parallel conductors carrying current in the same direction and the mutual repulsion of two carrying currents in opposite directions. The former case is shown in Fig. 115, the dotted arrows indicating the direction in which the two conductors will be urged, and the plain arrows indicating the direction of current. This effect can be plainly and easily shown by a very well known device. If a springy wire be coiled into a spiral, Fig. 116, and suspended so that its lower point just dips into a pool of mercury, when a current is sent through it the parallel conductors forming the spiral attract one another, and the spiral closes up a little. When the motion is sufficient to lift the point out of the mercury the circuit is broken, the current stops, and the attraction ceases. The point drops back into the mercury, the circuit is thus closed again and the whole operation repeats itself, the spiral jumping up and down in a very lively manner.

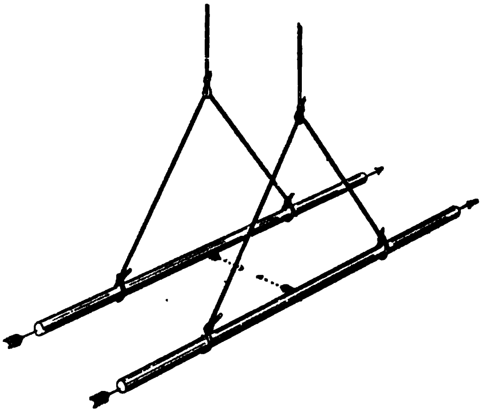


FIG. 115.—FORCE OF ATTRACTION BETWEEN TWO PARALLEL CONDUCTORS CARRYING CURRENT.

Not only are conductors carrying currents acted on by one another by virtue of their magnetic properties, but they are capable of being affected by steel magnets, or by magnetism however produced. Numerous interesting examples might be given, but they will be more clearly understood after the magnetic field and circuit have been dealt with.

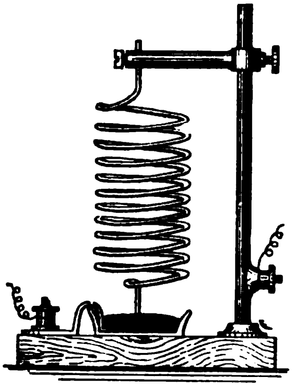


FIG. 116.—SPIRAL OF WIRE ILLUSTRATING ATTRACTION BETWEEN PARALLEL CONDUCTORS CARRYING CURRENT IN THE SAME DIRECTION.

CHAPTER II.—MAGNETIC FLUX AND FIELD.

A MAGNETIC CIRCUIT—LINES OF FORCE—RULES FOR DIRECTION—EWING'S THEORY OF MAGNETISATION OF IRON—MATERIALS OTHER THAN IRON—HYSTERESIS.

If we examine, by means of iron filings, the space in the immediate neighbourhood of a permanent magnet, as we did that of a wire carrying a current, we shall find that there are numberless forces at work all round the magnet, as there were round the wire, under whose control the filings arrange themselves in a remarkable manner. The result of such an investigation is shown in Fig. 117. The arrangement shown was obtained by the author using a steel magnet 8 in. long underneath a sheet of thin plate glass. It will be seen that there is no great difference in the disposition of the filings at the two ends of the magnet; that is to say, there is in the arrangement of filings nothing enabling us to say which end of the magnet is N. and which is S. The arrangement is quite symmetrical about the centre lines of the magnet. The arrangement is striking, however, and at once recalls the diagram given in Fig. 104. On comparing Figs. 104 and 117, several interesting points are at once observable. In the first place, the two ends of the magnet show the greatest activity while the middle is very ineffective. Next, the lines of filings in Fig. 117 appear to radiate from two points, whose position cannot be greatly different from the true poles. It was stated in the last chapter that the filings behave as small magnets, and it will be seen that this is true from an examination of Fig. 118. Here a number of small compass needles have been made to take the place of the filings on one side of the magnet. The compasses were of the "charm" type, pivoted between two glass discs. They were laid on a sheet of card below which was the magnet in the position shown by dotted lines. In that position they were photographed. On comparing Figs. 117 and 118, we see some differences. The filings show something that the compass needles do not. The filings are more thickly congregated at the two poles than at the middle of the bar, and the compasses give no corresponding effect in the picture. To show a corresponding effect we should have to start all the needles oscillating, say by jarring the table on which they lay, and we could then observe that those near the poles oscillate with great rapidity, while those further away do so more slowly, and those at the middle with extreme slowness.

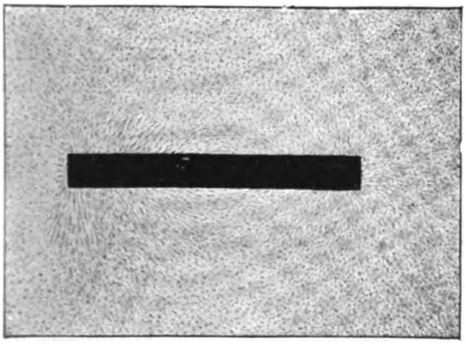


FIG. 117.—IRON FILINGS ROUND PERMANENT MAGNET.

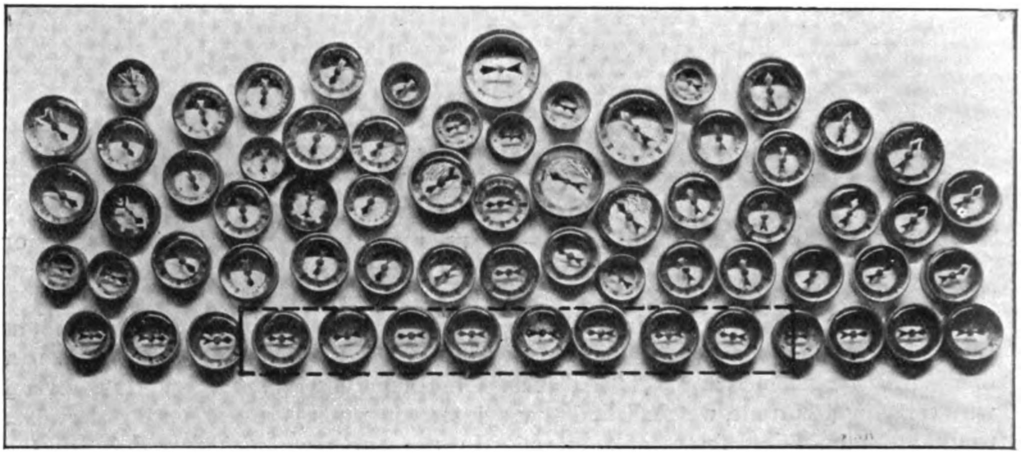


FIG. 118.—THE MAGNETIC FIELD OF A PERMANENT MAGNET, DISPLAYED BY COMPASS NEEDLES.

The filings are light, and therefore rather mobile, and are easily drawn by the magnet towards those parts which are strongest, hence their congregating at each end. The compass needles cannot be so moved, but the rate at which they oscillate on their

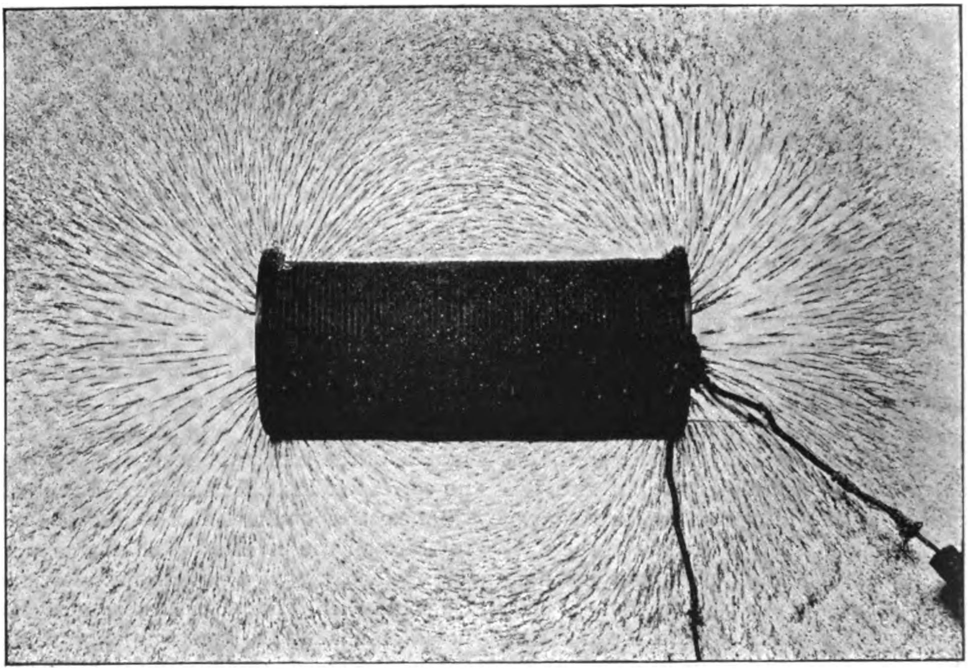


FIG. 119.—THE MAGNETIC FIELD DUE TO A CURRENT IN A COIL, DISPLAYED BY IRON FILINGS.

pivots is a measure of the strength of the forces controlling them, and hence they may be made to show, by their oscillations, the same facts which the filings emphasise. On the other hand the compass needles show something that the filings did not. If we start at any one compass needle and follow it along from the S. end to the N. end (the N. ends have arrowheads) we arrive at, or near, the S. end of the next, and if we jump the gap to the next, but always, on reaching it, pass along it from S. to N. we shall trace out a curve exactly similar to the curves of filings. The exact path depends upon where we start, but wherever we start our path always leads us away from the right-hand end of the magnet and towards the left hand. Now, since opposite poles attract one another, it follows that the end of the magnet to which the S. poles of the needles point is its N. end.

Yet another experiment. If we send an electric current through a coil of wire and explore the space surrounding it, just as we explored that surrounding a permanent magnet, either by filings or compass needles, we shall get almost precisely similar results.

This is shown in Figs. 119 and 120. The coil, however, gives us an opportunity for, and invites us to, an investigation which was not possible with the solid magnet; that is, "What goes on *inside* the magnet, or coil, either of which is capable of exhibiting such forces *outside* itself." By opening out the wires of the coil and spreading filings on a slip of cardboard which can be pushed into the coil, we get the result shown in Fig. 121. In Figs. 122 and 123 are shown the result of a similar inquiry, using compass needles. We have already seen that the filings curves *outside* the coil and the permanent magnet are practically identical, and, indeed, we can by many tests show that the space surrounding a permanent magnet is permeated by forces which are indistinguishable from those surrounding a coil of wire carrying a current. It is hence only reasonable to suppose that the *interior* of the permanent magnet is in a condition, if not precisely similar, at

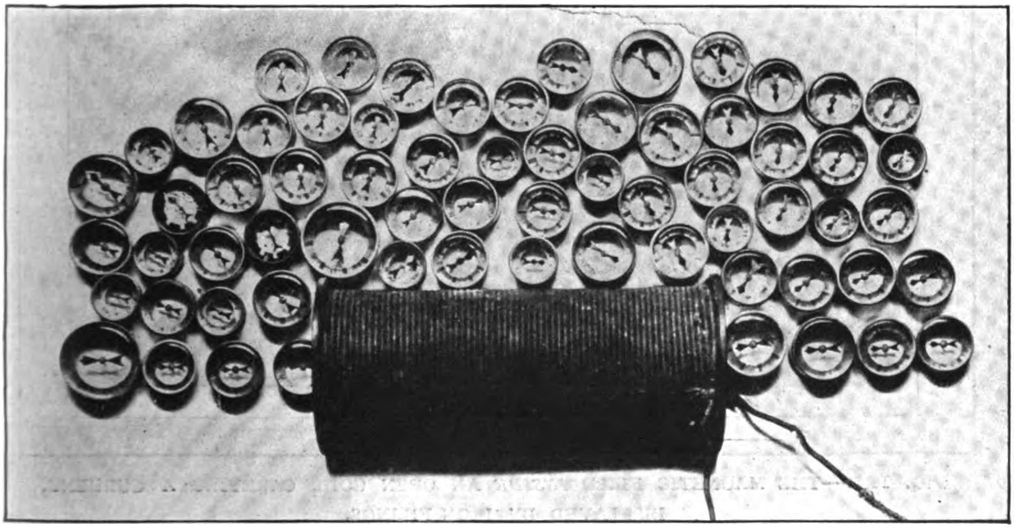


FIG. 120.—THE MAGNETIC FIELD DUE TO A CURRENT IN A COIL, DISPLAYED BY COMPASS NEEDLES.

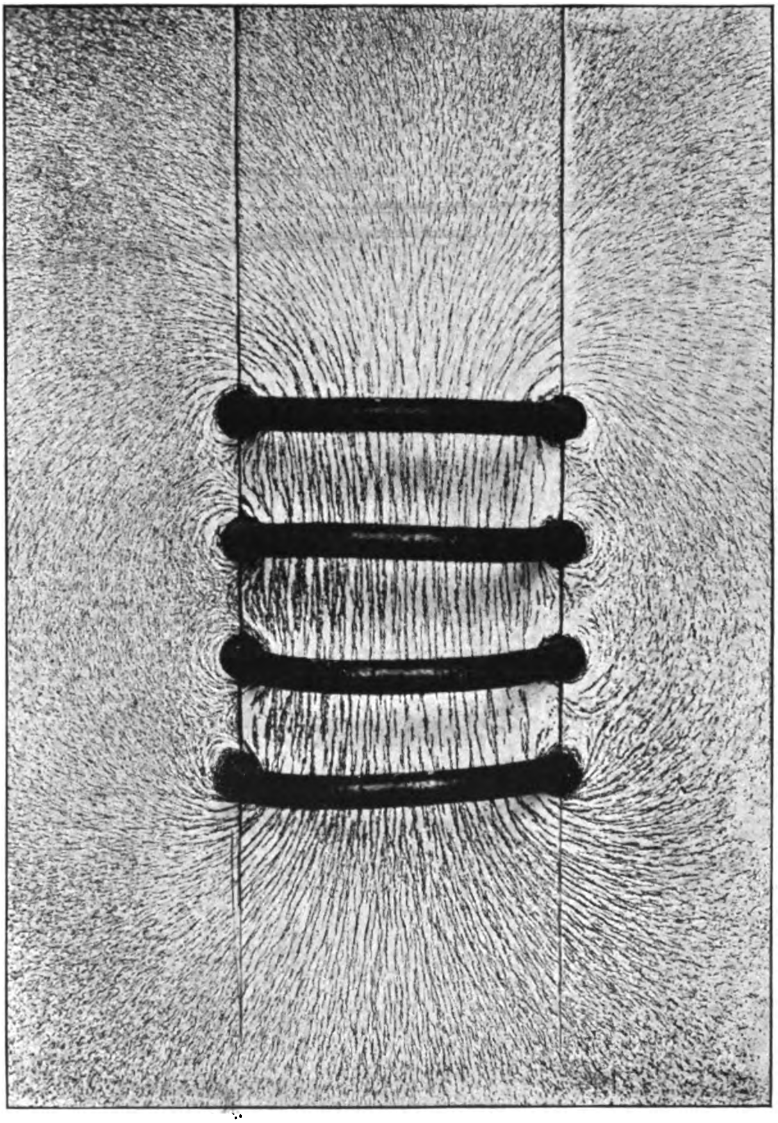


FIG. 121.—THE MAGNETIC FIELD *INSIDE* AN OPEN COIL, CARRYING A CURRENT, DISPLAYED BY IRON FILINGS.

least very similar, to that within the coil of wire.

One of the various ways of indicating the presence of magnetic forces, and one of the simplest, is to test and explore the condition of any particular region suspected of containing magnetic forces by means of a long thin magnet. A little reflection will show that since each compass needle shown in Fig. 118 is in itself a small permanent magnet, it is forced to take up a certain definite position by the magnetic forces because the north poles are all urged in one direction and the south poles in the opposite direction. This is only another way of saying that the N. pole of the permanent magnet attracts all the S. poles of the small ones and repels their N. poles (*see* page 168.) Or the converse might have been stated of the S. pole of the big magnet. We want just now, however, to dwell rather upon the space surrounding the magnet than on the magnet itself.

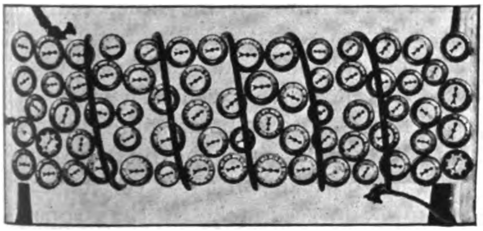


FIG. 122.—COMPASS NEEDLES ON GLASS IN A COIL OF WIRE—NO CURRENT IN THE WIRE.

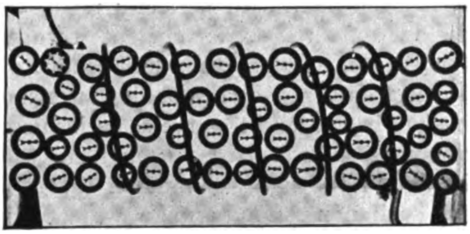


FIG. 123.—EFFECT ON COMPASS NEEDLES OF A CURRENT IN THE SURROUNDING COIL.

The region of space permeated by magnetic forces is called a magnetic field, and we may test for a magnetic field either by means of a north pole or of a south pole of a magnet. If we introduce a north pole into a field, it will be urged in one direction, whereas a south pole would be urged in the opposite one. By common consent the direction in which a north pole would be urged by a given field is called the direction of the field, and the whole phenomenon of a magnetic field has come to be regarded pretty much in the same light as that in which the electric circuit is. That is to say, it must not be supposed that the two are regarded as in any way identical, all that can be said is that we have two entirely distinct classes of phenomena, one magnetic and the other electric, the two having (each in its own sphere) striking points of similarity of behaviour, though not of essence. The two are, no doubt, closely connected, as we shall presently see, but it must never be forgotten that they are quite distinct.

A MAGNETIC CIRCUIT.

One of the most striking points of similarity between the two sets of phenomena is the fact that each is associated with what may be regarded as a circuit. Of the electric circuit we have already spoken in Section I. The magnetic circuit is very similar to it, and the whole phenomena of magnetism follow very similar laws, there being, however, one striking point of difference between them. This difference is that, while it is possible to completely insulate an electric circuit, it is absolutely impossible to insulate a magnetic one. This last statement needs a little further elucidation. As has already been seen, a north pole placed in a magnetic field is urged by the magnetic forces in a given direction, and from this fact the conception of a magnetic flux has arisen. The exploring north pole which is inserted into the field to test it is regarded as moving with—that is, in the same direction as—the magnetic flux, and hence the force on it is taken to indicate both the direction and sense of the flux. So far, this conception of magnetism is on all fours with the single fluid theory of electricity, the electric current passing, as we have seen, through what is, of necessity, a complete circuit composed of electric conductors. The point of difference to which we have just referred lies really in the fact that whereas certain substances have been found to perfectly resist the passage of an electric current through themselves, and are thus non-conductors of electricity, no corresponding substance has yet been found to serve as an insulator or non-conductor of magnetism, nor indeed, in the light of modern theory, is any such non-conductor likely to be discovered.

It was pointed out on page 179 that by starting at any one point in one of the curved lines, and passing along it, we should always travel from one pole of the magnet to the other. If we do this in the case of a coil through which an electric current is flowing, such as is shown in Fig. 119, we should find that on reaching what we may call the pole of the coil, our line would lead us into and through the coil and out at the other end. There we should find ourselves on the old path again, and that, as a matter of fact, every line forms a closed loop.

A very convenient way of mapping out the lines of force of permanent magnets devised by the author is as follows:—A small compass needle of the charm type is taken, and a disc of cardboard cut to the exact size of the compass case, and in the centre of the disc a hole is made. If, now, the compass be placed on the disc and the two are laid on a sheet of cardboard near the magnet, the needle will, of course, take up a position indicating the general direction of the field at its centre. The point where the north pole of the needle appears to cut the edge of the disc is then marked on the sheet of cardboard. The compass is now lifted off the disc and the disc is shifted so that the mark just made on the sheet of cardboard can be seen through the hole in its centre. The compass is then replaced on the disc and a new mark made where the north pole of the needle now appears to cut the edge of the disc. The disc is then again shifted so that the last made mark is seen through the hole, and the operations are repeated. The marks thus made on the sheet of cardboard when joined together give excellent curves. It is well to start at a point at some distance from either pole, since the lines close to a pole are so packed that it is very difficult to follow one accurately in that region. When one end of the magnet has been reached the compass can be started again at the first point and worked towards the other end, using the other pole of the needle.

LINES OF FORCE.

These lines were called by Faraday lines of force; and, since the force on an exploring magnet pole acts not only along one of these definite lines, but in one sense (that is, in one direction) along that line, that is to say, since a north magnetic pole placed in a field will always be urged along one of these lines in the *same* direction, our conception of the whole magnetic field must take this fact into account. We now, therefore, regard that region of space in which there is a magnetic field as being just as fully permeated by forces as is, say, the space in a corridor through which a strong draught is blowing. The corridor is *permeated* with wind forces. Now the forces due to the draught could very easily be shown by numerous little weathercocks up in the corridor, or by throwing dust into the air, and it is easily seen that if light particles were thrown into the air they would float along pretty much in definite stream lines. No one would suppose from the fact that there are gaps between these stream lines that there is no draught in the gaps, and similarly, in the magnetic field as mapped out by the iron filings, we must not suppose that there are no magnetic forces in the gaps between the lines of filings. At the same time the density with which the filings congregate is a very fair indication of the strength of the magnetic field, that is, of the force which a magnetic north pole placed there would experience, and Faraday suggested that the magnetic field should be regarded for purposes of calculation as actually consisting of these lines of force.

The magnetic field has thus come to be treated in calculations as consisting of a very great number of lines of force which, in the case of a permanent magnet may be said to protrude from the poles like the bristles of a brush, and the strength of the field is indicated by the closeness with which the bristles are packed. If we wish to make a numerical examination of the strength of the field at different parts, we might take a little loop of wire, bent, say, into the shape of a square, whose sides are one centimetre long, and test at various parts of the field how many of the bristles, or lines of force, the little square of wire could be made to enclose. If it enclosed ten we should say the field was of strength ten lines per square centimetre, and so on.

RULES FOR DIRECTION.

Up to the present we have only considered the magnetic effect of a current flowing in a straight wire, and though we have seen what a coil does, it remains for us to analyse the magnetic effect of a current when it flows through a coiled wire. The result with a straight wire is given in Fig. 124, in which the current is flowing *down* the wire. From this we deduce the rule that if we look along the wire *in the direction in which the current is flowing*, so that the current flows away from the observer, the little compass needles placed round the wires show that the direction of the magnetic forces produced by the current is that of a circle surrounding the wire, and that if we trace the compass needles round, always entering a needle at the south end and leaving it at the north, we should travel round the circle in the *same direction as the hands of a clock*.

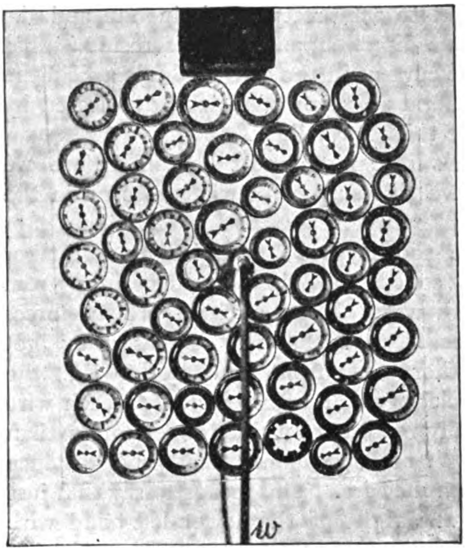


FIG. 124.—THE DIRECTION OF MAGNETIC FORCE DUE TO A *DOWNWARD* CURRENT.

Now let us consider what the effect of coiling a conductor will be. In Fig. 125 two turns of a coil are shown in section, together with a diagram of the circular forces due to each wire when undisturbed by its neighbours. It is here seen that the gap between two neighbouring wires contains just as many forces acting downwards as there are acting upwards, while the space in the inside of the coil contains forces which, on the whole, all act in one direction. Outside the coil, also, the forces all tend to act pretty much in one and the same direction, and the net result is that the current in the coil produces a field the general direction of which is indicated by the thick wavy line.

A little more must be said before we leave this subject of what goes on in the gap between any two wires. The gaps are shown to be occupied by a number of concentric circles emanating from each wire. These circles represent forces whose strengths fall off as they get farther away from the wire, so that the circles of small diameter close to each wire really represent much stronger forces than those of large diameter at some distance from the wire. This means to say that just to the right of the lower left-hand wire we have strong downward forces due to that wire opposing weak upward forces from its right-hand neighbour, and near the right-hand neighbour we have strong upward forces due to the latter opposed by weak downward forces due to the left-hand wire. If the two wires, therefore, are separated by any appreciable difference, there is a tendency, no doubt, for what may be called a little eddy, but if the wires are closely packed in the coil these may be neglected. There is one other consideration which must not, for accuracy's sake, be overlooked. It is that although the circles around each wire are drawn in the illustration only in the gaps between it and its neighbours, the forces really extend indefinitely in each direction, so that, properly speaking, others should be drawn round each wire, extending to and affecting all the other gaps and wires of the coil. A few of these have been drawn round the upper left hand wire. For the proper investigation of this subject the student is referred to mathematical treatises on magnetism, it being sufficient for the scope of the present work to point out the practical result, namely, that the turns all assist to produce, through the centre of the coil in the direction shown, a field which opens out and returns outside the coil on every side. A fair mechanical model of the field would be obtained by binding string tightly round the middle half of a bundle of fine wires, and then bending the protruding free ends back over the string and joining the two ends of each individual wire together. The string would represent the coil with a current in it, and the wires the lines of force.

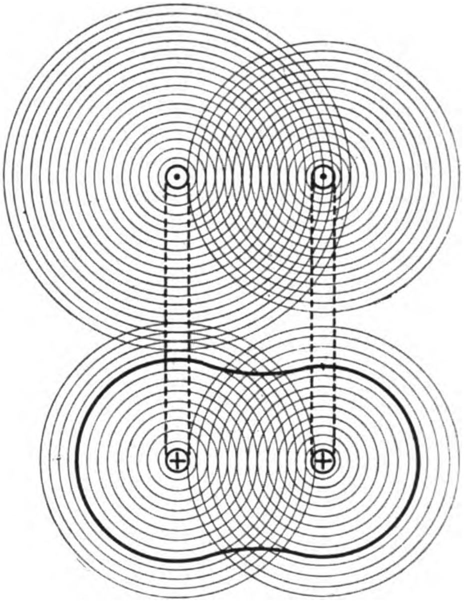


FIG. 125.—DIAGRAM OF CIRCULAR FORCES DUE TO CURRENT IN TWO TURNS OF A COIL.

It is of great importance in practical work to be able to determine at once what will be the direction of the field produced by a coil when the direction of the current though the coil is known. We have already stated that by "direction of a field" is meant the direction in which a free north magnetic pole would be urged. Hence the direction of the flux inside the coil, Fig. 125, is from left to right, and outside the coil from right to left. The coil thus acts like a permanent bar magnet whose N. pole is at the right-hand end, and we may define any surface through which lines of force are passing as being north on that side at which the lines come out, and south on that side at which the lines go in.

Fortunately we have an extremely simple rule for determining the connection between the directions of current and flux. We have two directions to consider, the direction of the current, and the direction of the flux it produces, and one of these may always be considered as a straight line direction, and the other as a circular direction in a plane at right angles to the straight line. In the case of a straight wire it is the current that has a straight line path and the magnetic flux surrounding the wire has a circular path; in the case of the coil it is, of course, the current which has the circular path, while the magnetic flux inside the coil has the straight line path. Now in everyday life there is a very familiar object, namely, the screw, which possesses circular motion and straight line motion. If a screw is rotated it travels in a straight line direction at right angles to the plane of rotation, thus perfectly representing the two directions of motion which we want to consider. Now, further, positive direction of current and positive direction of flux have been fortunately so chosen that the ordinary screw, such as a carpenter uses, and which the engineer calls a right-handed screw, represents by its movements the directions of current and flux. If we apply this to the case of a current in a straight wire, we imagine a screw which we wish to make travel in the direction of the current; then the direction in which we should have to rotate the head of the imaginary screw gives us the direction of the circular magnetic flux produced round the wire by that current. In the case of the coil, the direction of travel of the screw represents the direction of the travel of the magnetic flux through the coil, while its direction of rotation represents the direction of the circulation current round the coil. We thus have only to know in the case of a straight wire which end the current enters at, and in the case of a coil whether the current is going round it "clockwise" or "counter clockwise," to determine what will be the direction of the magnetic flux produced in each case. These facts are made clear by the diagrams in Fig. 126.

MAGNETISATION OF IRON.

If an insulated wire be coiled round a rod of iron and a current be sent through the wire, the iron is, of course, subjected to the magnetic forces set up within the coil. Now we have already seen that magnetism is regarded as a flux and that *all* substances act as conductors of the magnetic flux. Air is one of the poorest of magnetic conductors, whereas iron is the best. Iron, however, does not exhibit a constant power of conduction, but falls off in conducting power as it is made to carry more lines of force. These facts have been known for a great while, and if a curve be plotted whose vertical ordinates show the total flux being carried by the iron, and whose horizontal ordinates show the strength of the magnetising forces, we get a curve of the general shape shown in Fig. 127. The shape of this curve remained for a long time unexplained until Professor Ewing brought forward his theory of the magnetisation of iron.

According to Professor Ewing, iron may be considered to consist of a vast aggregate of minute molecular magnets, each molecule of the iron being considered to be a minute permanent magnet having a north and south pole of its own. In the unmagnetised state of the iron bar, these little molecular magnets arrange themselves in what may be called higgledy piggledy fashion, and set themselves in groups variously arranged and of various dimen-

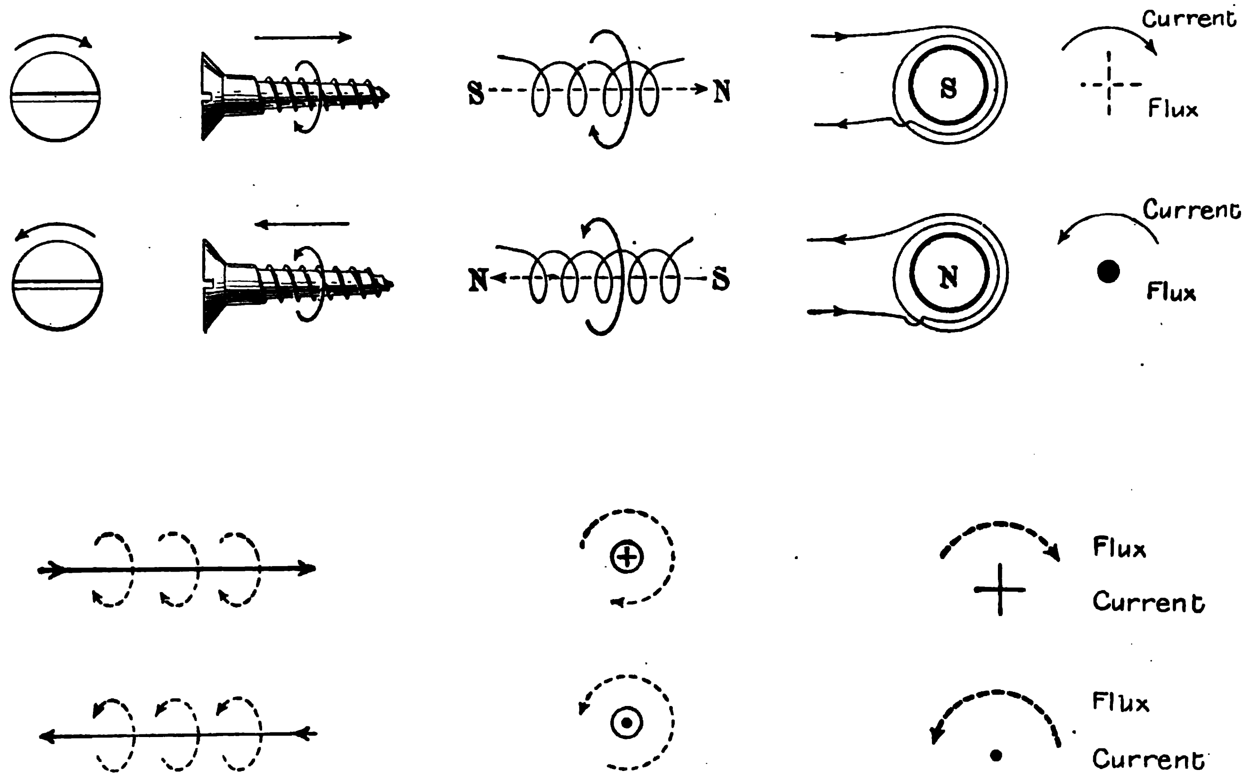


FIG. 126—DIAGRAM ILLUSTRATING THE CONNECTION BETWEEN THE DIRECTION OF FLOW OF CURRENT AND THE DIRECTION OF THE MAGNETIC FLUX PRODUCED. A + INDICATES THE TAIL AND A ● THE HEAD OF AN ARROW.

sions, but all such that, starting with the flux coming out from the north pole of one molecular magnet, we enter the south pole of a neighbour, out at its north pole into the south pole of another, and so on, coming back to the point at which we started. Thus the iron as a whole shows no magnetic force, since the forces of the individual molecules are all arranged in closed circuits somewhat as has been indicated in Fig. 128.

If now all the molecules are subjected to the action of a coil surrounding the bar, the effect is to make them all point in one direction, just as a number of compass needles (if not placed too close together) in the magnetic field of the earth all point to the north pole. The effect, then, of sending a current through the coil round the bar of iron is, so to speak, that of breaking up the little groups or parties of molecules and combing them out so that all their north poles point in one direction, as in Fig. 129. Now all the little parties will not hold together equally firmly, but some are more readily broken up than others; hence when a weak magnetising force is applied it may serve to break up a few of the parties, those whose members hold weakly together, but it may not suffice to break up those whose members are firmly attached to one another. The latter can only be broken up by stronger forces, but as soon as the bond is once broken all the individuals are at once fairly free and the result is that as each bond is broken a number of molecules begin to swing round and point in the same direction. As soon as a molecule points in the direction of the magnetic force of the coil it adds its little quota of magnetic flux to that which the coil itself would produce if no iron were there; hence the breaking up of a group of molecules means the addition of a considerable flux to that which was existing before. As the magnetising force increases more groups are broken up, and the individuals "combed out" in the right direction; gradually there remain fewer and fewer to break up, those remaining being the most strongly built, until at length all the molecules in the iron are pointing in one direction. When this point has been reached any further increase of magnetising force can have no effect on the iron, and we should expect the coil to behave from that point on as though no iron were present.

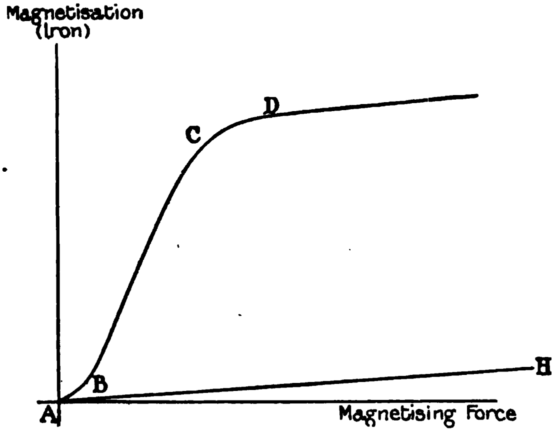


FIG. 127.—TYPICAL CURVE OF MAGNETISATION OF IRON.

Now let us see how this theory will fit with the observed results. If we look at the curve in Fig. 127, we see that it may be divided into three main portions, each of which is approximately straight and which are marked A-B, B-C, and C-D on the figure. The first, which is very short, may fairly be supposed to correspond to the breaking up of the feebly coherent groups by a weak magnetising force. Then, as the magnetising force is increased the more strongly cohering groups are broken up and throw their own magnetism into the balance, thus causing a very rapid rise in the total flux traversing the iron. This stage is shown in the part of the curve between B and C. At C the curve begins

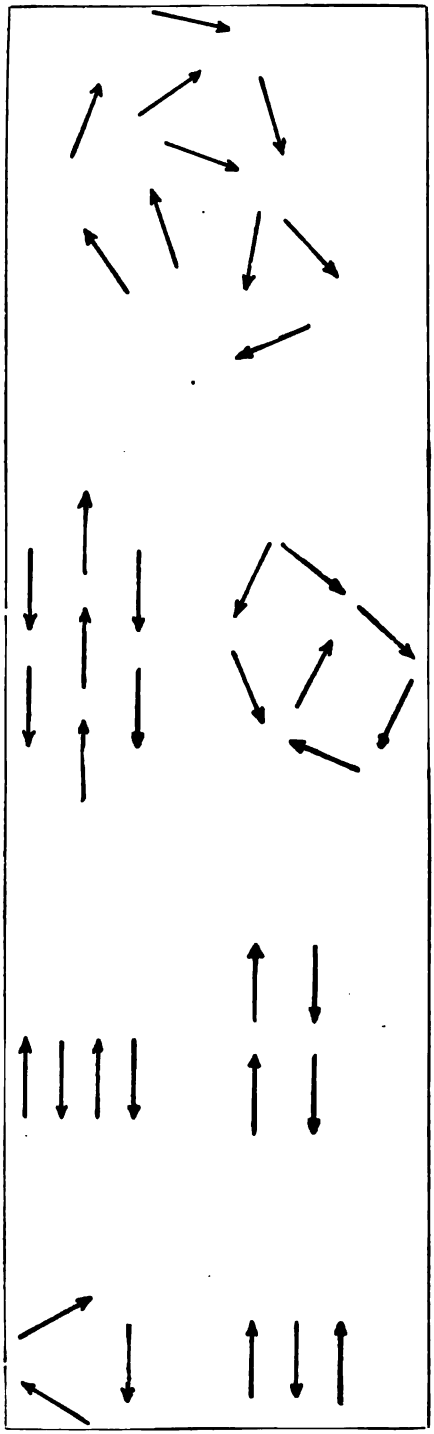


FIG. 128.—DIAGRAM ILLUSTRATING GROUPS OF MOLECULAR MAGNETS IN UNMAGNETISED IRON.

to bend over, and this is regarded as corresponding to the stage where nearly all the groups have been combed out, leaving only a few more stubborn ones, which very gradually yield as the magnetising force is increased till the point D is reached. At the point D there remain no more groups to be broken up and all the molecules are combed out nearly straight, so that from the point D onwards the curve rises no faster than it would have done had there been no iron in the coil at all. The straight line drawn at H shows the rise of magnetic field that would have been produced in the coil had there been no iron at all present, and it will be seen that the slope of the iron curve after the point D has been reached is the same as that of the line H.*

This theory, therefore, fits the facts extremely well, and not only does it do so by examination of the curve, but Professor Ewing constructed a very large coil similar to that shown in Fig. 121, and placed a very great number of small pivoted compass needles within it. On sending a current of gradually increasing strength through the coil he was able to observe the gradual break-up of all the little groups into which the needles had set themselves, arriving finally at the point when all the compass needles were combed out just as has been indicated above.

The curve of magnetisation of iron is by no means the only fact which corroborates Ewing's theory. It might well be urged that if the molecules are to swing round on some imaginary pivot under the magnetising action of a coil carrying a current, they will occupy more space than when packed closer together in what has been called a "higgledy piggledy" arrangement, and that if this contention held good

* In point of fact this can only be shown on the diagram by a change of zero when the point D is reached, since the height of the point D is some 18,000 times as great as that of the point on H vertically below it.

the bar of iron when magnetised should be longer than when unmagnetised. This has been shown to be the case : slight elongation occurs during the earlier stages of magnetisation, but at high values of **B** the iron begins to contract, and will even become shorter than the original unmagnetised length. The amount of elongation is extremely small, it being only about one four-millionth of the length of the specimen.

MATERIALS OTHER THAN IRON.

There are three materials whose behaviour in a magnetic field is of very great interest; two, viz. nickel and cobalt, behave similarly to iron, having permeabilities of 25 and 75 respectively at a **B** of about 5,000.

A change occurs in the value of the electrical resistance of the metal bismuth when placed in a magnetic field, being practically proportional to the strength of the magnetic field.

A neat piece of apparatus is constructed to act upon this principle. It consists of a very fine spiral of pure bismuth wire coiled like the hair spring of a watch and placed between two thin slips of mica, which afford both mechanical protection and electrical insulation. This thin flat spiral, may be readily inserted in an air gap in any field, and by a measurement of its resistance when there the value of the field strength may be ascertained.

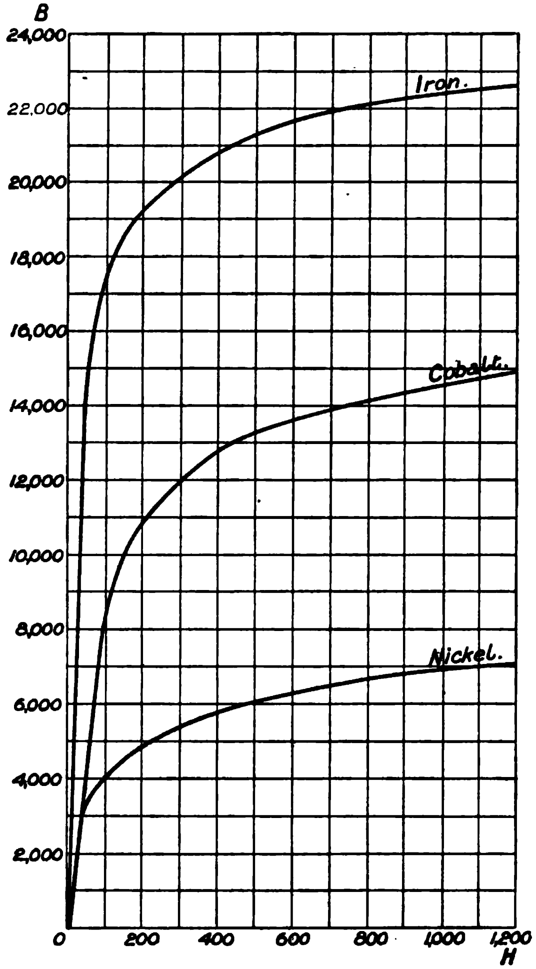


FIG. 129.—MAGNETISATION CURVES FOR COMPARISON OF NICKEL, COBALT, AND WROUGHT IRON.

A curve is furnished by the makers with the instrument, showing the connection between the resistance of the specimen and the field strength. Other materials also show this peculiar property, nickel being one which shows it in prominent degree. The magnetic field may be applied either along the line of flow of the current, or transversely to it, and Professor C. G. Knott has shown that if the nickel be in the shape of wire the effect of weak fields is not very marked, although with nickel in the shape of very thin tape the effect may be readily observed. A curious point in this connection is that the width of the tape has a pronounced influence upon the effect of the magnetic field when the field is low, the wider tape giving a more pronounced effect than the narrow.

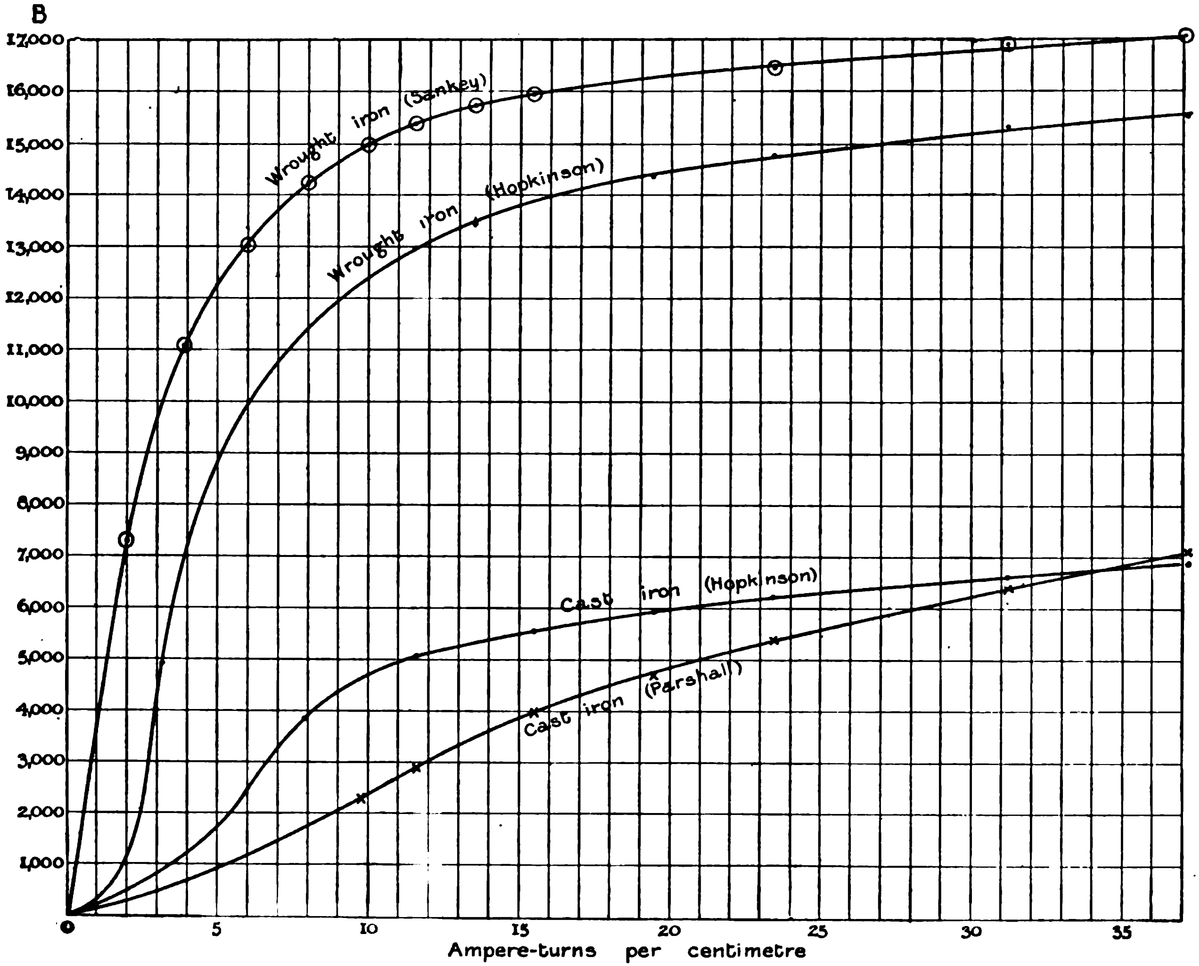


FIG. 130.—MAGNETISATION CURVES FOR WROUGHT AND CAST IRON.

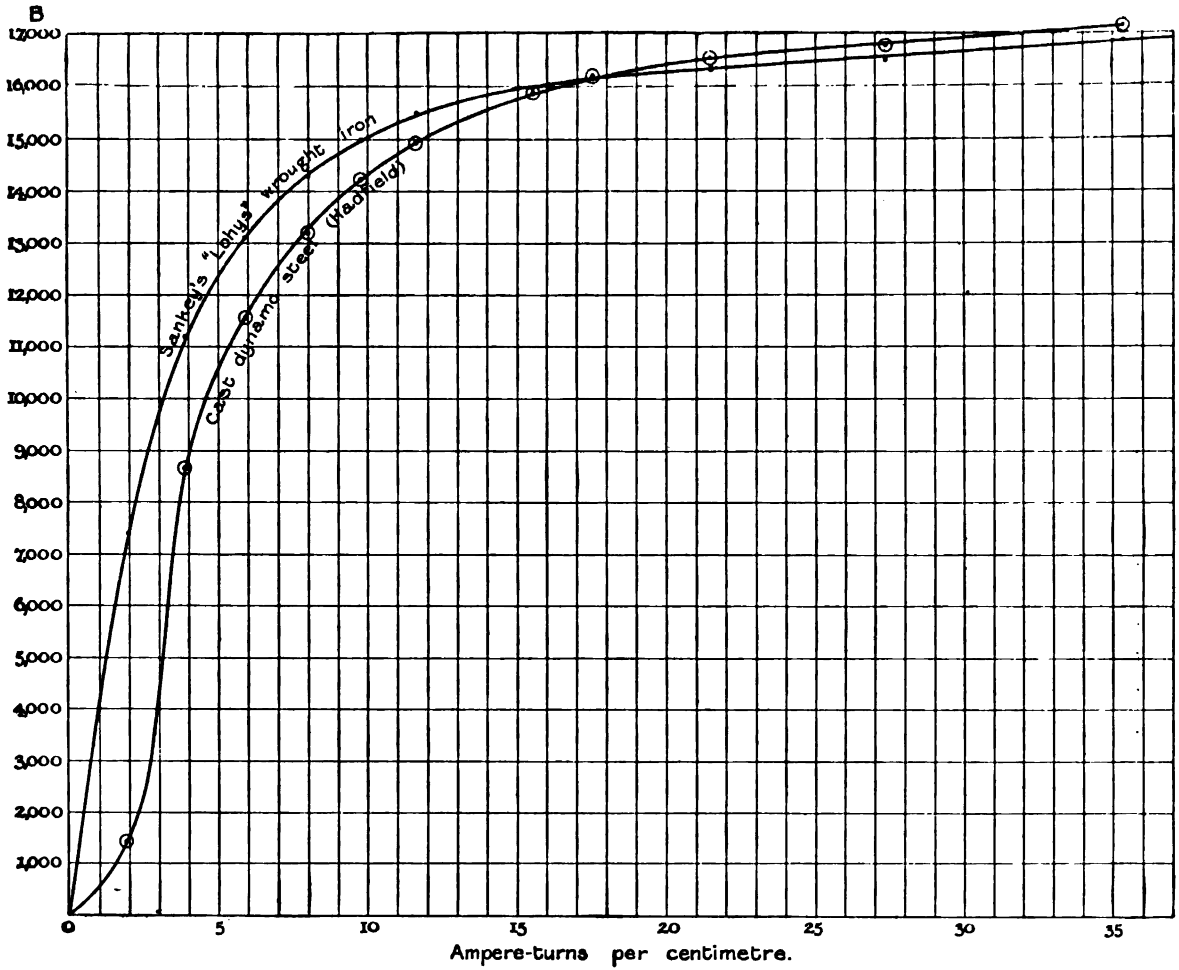


FIG. 131.—MAGNETISATION CURVES FOR WROUGHT IRON AND CAST STEEL.

CHAPTER III.—THE MAGNETIC CIRCUIT.

MAGNETIC OHM'S LAW—PERMEABILITY—ENERGY OF MAGNETISATION—HYSTERESIS—ENERGY OF HYSTERESIS — SOLENOIDS — THE PULL OF ELECTROMAGNETS — WINDING—NUMERICAL EXAMPLES—CRANE MAGNETS—BELLS—AND MAGNETIC APPARATUS.

WE have already referred, on page 181, to what is called the magnetic circuit, and this now requires further consideration. The magnetic flux, which is the analogue of the electric current, consists, as we have seen, of a number of lines of force, each of these lines being closed upon itself. A certain magnetic effort is necessary to set up this magnetic flux, or, in other words, a magnetic field cannot exist apart from a magnetising force, whether the field be in the air or inside a steel magnet. The magnetising effort or force is called a magnetomotive force, and since the lines of the flux are always closed upon themselves, it is an obvious step to suppose the magnetomotive force as being really a difference between two magnetic potentials, the potential changing steadily from point to point along the flux. Hence we come to consider the flux as possessing at one point a certain magnetic potential, and as gradually losing that potential round the circuit, just as a current loses potential as it traverses the electric circuit. There is then between any two points of a magnetic line a difference of magnetic potentials, and the magnitude of this difference will depend upon the distance between the two points and upon the material or medium which the line traverses, just as the difference of electric potentials between two points in a conductor depends on the distance between the two points and upon the material of the conductor. It also depends on the strength of the field, that is, on the "flux-density," but this is assumed constant in the above statement. We thus have a kind of Ohm's law for magnetism which brings us under the necessity of defining the three quantities, which we shall call respectively (1) magnetic current or flux, (2) magnetomotive force or magnetic potential difference, and (3) magnetic resistance. If we are to define these so as to obtain simple numerical relations, as in the case of the electric circuit (page 22), we must not only define the quantities, but must fix on suitable units for their measurement.

In view of the striking significance of the crowdedness or density of the iron filings, and the closeness with which the lines they mapped out were packed together, Faraday suggested that the strength of the magnetic field should be spoken of as being represented by the closeness with which these lines are packed, and the total flux by the total number of lines. Since, however, the sheet of cardboard carrying the filings only shows the lines in the plane of its surface, (although there are lines permeating the whole space surrounding it), it becomes necessary to speak, not merely of the closeness of the lines on the cardboard, but of the closeness with which they are packed in *space*. By laying a rule across the lines mapped out by filings, and counting the number of lines covered by an inch of the rule, we could obtain a value for what we might call the "lines per inch." We have to speak, however, not of the lines per inch *in a plane*, but of the lines per square inch *through a surface*, and we refer to a surface placed at right angles to the general direction of the lines. This is shown diagrammatically in Fig. 132 where the lines coming out from the magnet are shown passing through a little loop of wire forming a square whose side is, say, one inch. It must not be supposed that the lines have any material existence, any more than the stream lines shown by leaves or dust in the road on a windy day indicate the presence of anything material. They merely show the *direction of the force* of the wind at the place just where they happen to be. We have, merely for purposes of numerical treatment, conceived the lines to have a material existence, but it would be equally right or wrong to suppose the stream lines of the wind to be material things, and to speak of the strength of the wind as so many lines per square yard. The next question is, How strong a field are we to represent by our imaginary one line per square inch? As a matter of fact, although we have spoken of a square inch, the unit taken for all scientific work is the centimetre; and hence we must now speak of one line per square centimetre, which is equivalent, of course, to 6·45 lines per square inch. If our "one line per square centimetre" is to stand for a field of unit strength, we have to decide what strength of field we will regard as a unit for measurement before we know the meaning of the term "one line per square centimetre." If there were such a thing as a material line we could, of course, experiment with a field of one per square centimetre and carefully measure some of the effects it would produce, and define our strength of field from that. Failing this, we have to fall back upon some other way of defining a unit strength of field, and, having found that strength, we say it shall be represented in all our quantitative work by one line per square centimetre. The field which has been adopted, and which has been defined as of unit strength is that field in which a free single magnetic pole of unit strength will experience a force of one dyne driving it along (see page 181). The total field or flux is the total number of lines. For the definition of a unit magnetic pole the reader is referred to the chapter on units. It will thus be seen that our definitions of unit field strength and unit field are rational, because they fall into line with other defined units; while the representation of the field by one line, and of the field strength by one line per square centimetre, is quite arbitrary. If the strength of field were such as to produce a force of 150 dynes on an exploring pole of unit strength, we should say the field strength was 150, and should agree that it be represented by 150 lines per square centimetre. The total field or flux depends on the area of cross section at that strength. The field strength is always indicated by the letter **B**, and it is quite usual to speak of "a **B** of 1,000," meaning, of course, a field strength of 1,000 dynes or of 1,000 lines per square centimetre. The letter N is very commonly used for the total field. The name "gauss" has recently been given to a field strength of one line per square centimetre, and the name "maxwell" to a total field of one line. Hence a field of one kilogauss would exert a force of 1,000 dynes on a unit pole, and if the cross section of the field were 20 square centimetres, there would be a flux of 20 kilomaxwells.

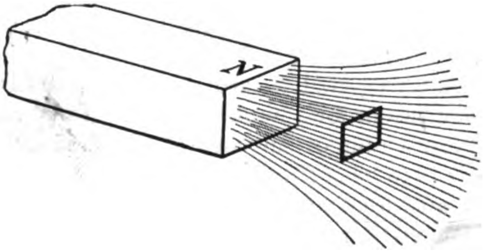


FIG. 132.—DIAGRAM ILLUSTRATING FLUX DENSITY OR "**B**."

The next quantity we have to deal with is the magnetomotive force or magnetic potential difference. Since we are only concerned with potential differences, as in the electric circuit, and not with absolute potentials, we will only speak here of potential differences, the consideration of absolute magnetic potential being deferred until we take up the whole question of units in the chapter on units. Having once obtained the standard of measurement for the strength of a magnetic field, we can very easily deduce a standard for the measurement of magnetomotive force, if we are prepared to assign to some material the property of unit specific resistivity to the magnetic flux. The necessity for this arbitrary action can be understood by remembering that we are trying to establish foundations for a numerical law. If we are given a unit of current or flux and our law is to be of the shape

$$\frac{\text{Magnetomotive force}}{\text{Magnetic resistance}} = \text{magnetic flux},$$

the fraction on the left hand side of the equation will fall into units at once if we can give either denominator or numerator unit value, since we have a unit for measurement of field. Now all the magnetic effects with which we are familiar are capable of being transmitted through the medium of air, and, as has already been pointed out, with the exception of comparatively few materials, all ordinary substances act practically as air does. Hence for convenience the specific resistivity of air to a magnetic flux has been assigned unit value, and now, having this standard for magnetic resistance and a standard for unit magnetic flux, the standard for magnetomotive force follows from simple experiment. It remains, therefore, for us by experiment to determine what magnetomotive force will produce a unit flux in air. Experiment shows that if we take a coil of wire and send a current through it, if the coil be long in comparison with its diameter, the field anywhere inside that coil, except in the neighbourhood of the two ends, is of a *strength* represented by

$$\frac{4\pi}{10} \times \frac{A \times T}{l}$$

so that the total flux is known if the area a of the cross-section of the coil, in square centimetres is known. The flux then is

$$\frac{4\pi}{10} \times \frac{AT}{l} \times a \quad \text{or} \quad \frac{4\pi \times AT}{10} \div \frac{l}{a}$$

In these expressions, A is the current in amperes passing through the coil, T the number of complete turns or spirals in the coil, l the length of the coil in centimetres, and a its area of cross-section in square centimetres.

The last expression readily falls into two parts, the first of which is divided by the second. The first comprises a mere numeric $\frac{4\pi}{10}$ (or 1·257) and two variables, A and T. The product of these two variables is called the number of ampere-turns in the coil; one ampere-turn being the product of one ampere through one turn or the tenth of an ampere through ten turns, or of any other combination of amperes and turns which will give unity as their product. Experiment shows that the field produced by a given number of ampere-turns in a given circuit is quite independent of the way that number is obtained; that is to say, it does not matter what relation A and T have to one another so long as their *product* is of the right magnitude. The flux being thus directly proportional to the ampere-turns, they may rightly be regarded as the magnetomotive force and the quantity $\frac{l}{a}$, to which the flux is inversely proportional, as magnetic resistance.

The magnetic resistance is usually spoken of as "reluctance" in order to avoid confusion between magnetic and electric resistance. Reluctance to the passage of a magnetic flux is found to vary with the length and inversely as the area of the path, a connection which we also found to hold in the electric case (*see* page 12). If we indicate magnetic reluctance of a path by R_m, then we have, for the value of the reluctance, the expression $R_m = \frac{l}{a}$ for air. A path of unit magnetic reluctance would thus be an air column one centimetre long and one square centimetre in cross-section. The expressions given above show that through this a total flux of $\frac{4\pi}{10}$ AT lines would be produced, and hence, by our definition, the unit of magnetomotive force would be $\frac{1}{1\cdot257}$ or practically 0·795 of an ampere-turn.

Now, while this gives us the units we need for the direct application of the law,

$$\frac{\text{Magnetomotive force}}{\text{Reluctance}} = \text{Flux},$$

it is necessary to speak of a different form of the law which is more commonly used. It is usually of considerable importance to know at once, not the flux, but the flux density, or what we have above called the field strength. The flux density in lines per square centimetre is generally denoted by the letter **B**, and if we use N for the flux, and *a* for the area of cross section or its path, then obviously

$$\mathbf{B} = \frac{N}{a}$$

and substituting we get

$$\mathbf{B}_{air} = \frac{N}{a} = \frac{4\pi\,AT}{10} \times \frac{a}{l} \times \frac{1}{a} = \frac{4\pi}{10}\frac{AT}{l}$$

$$\text{or } \mathbf{B} = 0{\cdot}795\,\frac{AT}{l} \text{ in air.}$$

Examination of this result shows that the *flux density* inside any given hollow coil is proportional to the quantity $\frac{AT}{l}$ which clearly stands for the number of ampere-turns per centimetre of length. The length referred to, if we consider the middle part of the coil only, is clearly the length of path for the flux; in other words, the flux which traverses a centimetre of length inside the coil is forced to do so by the magnetomotive force of the ampere-turns encircling that centimetre. Or we may state that between the two ends of that centimetre there is a difference of magnetic potentials due to the difference in the number of ampere-turns at work at the two ends, the difference being, of course, the number of ampere-turns encircling that centimetre. Magnetomotive force thus can be expressed in terms of the ampere-turns at work on each centimetre of the path of the flux, and the quantity obtained by multiplying the ampere-turns by the expression $\frac{4\pi}{10\,l}$ is usually denoted by the letter H. This is the unit in which magnetomotive force is generally expressed; it expresses the magnetomotive force in terms of the *flux density* that it would produce *in air*. This flux density is always symbolised by the letter H, and is numerically equal to

$$0{\cdot}795\,\frac{AT}{l}.$$

Since, however, there are materials which act, some as better, some as worse, conductors than air for magnetism, we have, in dealing with the reluctance of such materials, to introduce some factor which shall express the relative conductivity of these materials as compared with air. This relative conductivity is called the permeability of the material and is indicated by the symbol μ.

Thus in air the relation between the magnetomotive force, expressed by H, and the flux density which we have called **B**, is that they are equal; the permeability of air being, as we have seen, 1; hence for air $\frac{\mathbf{B}}{H} = 1$, but for any other material the magnetomotive force H will not produce a field of strength H, but a field whose strength is H multiplied by the factor μ, the value of μ being dependent on the material in use. Hence with such materials

$$\mathbf{B} = \mu \text{ H}.$$

PERMEABILITY.

In addition to the fact that the reluctance of the ferromagnetic materials, iron, nickel, and cobalt, is so very much less than air, they are further differentiated strongly from air in their magnetic behaviour, seeing that while the reluctance of air is constant, the reluctance of these materials varies with the flux density. We have above referred to the occasion for air being taken as the standard magnetic material for comparison, and this is not only due to the fact that it is always at hand as a standard for comparison, but also to the fact of its constancy of reluctance. In dealing with magnetic calculations it is more common to speak of that magnetic property which corresponds with conductivity in electrical calculations, the term "permeability" being given to the magnetic property.

Until recent years the material of highest known permeability was pure annealed wrought iron, the iron prepared in Sweden and smelted with charcoal standing above all other brands. The cause of this excellence has been attributed to the presence of foreign matters in the coke used in smelting in this country (owing to the high cost of charcoal here) which resulted in a less pure brand of iron, with a consequent lowering of its permeability. Within recent years, however, even Swedish charcoal iron has been displaced to a large extent by a material which is in reality a cast steel. It is an exceedingly low carbon steel, having only about 0·08 per cent. of carbon; the presence of the carbon enables castings to be made fairly easily while it does not lower the permeability. Until these steels had been developed, as they now have been by various steel masters, notably by Hadfield, Edgar Allen, and Krupp (of Essen, Germany), the universal standard for comparison was a brand of wrought iron which had been tested by the late Dr. Hopkinson with very great care and accuracy. All the modern brands of iron sold for magnetic use are very considerably superior to that which was tested by Dr. Hopkinson, a particular brand of sheet iron produced by Sankey (and designated Lohys by him) being very greatly superior to the standard brand of Hopkinson, not only at the lower flux densities, but well up above what is called the knee of the curve. In the diagram (Fig. 130) shown already on page 191, are given four curves, showing the degree of magnetisation produced in four brands of iron, under varying magnetomotive forces. The upper, as marked, relates to Sankey's Lohys sheet iron, and near to which is shown also Hopkinson's wrought iron. The two lower curves relate to cast iron, one representing results obtained by Hopkinson of grey cast iron and the other results given by Parshall.

Having reference first to the two curves for wrought iron, it will be seen that both rise very rapidly and almost along straight lines up to a value of about $\mathbf{B} = 12{,}000$, from which they begin to bend over with an increasing diminution in slope until a value of about 14,000 is reached in the case of Hopkinson and about 16,000 to 17,000 in Sankey's iron. The portion lying between these limits is generally known as the knee of the curve, while the upper limit is generally referred to as the saturation point. In both cases it is to be noted that beyond the saturation point the continued upward slope of the curves is not greatly different from the slope of air. The fact that the permeability for air is constant accounts for the simple straight line representing the magnetisation of air in the curve, while the variable slope of the iron curves at once indicates the variation in permeability. In Fig. 131 a comparison is made between Sankey's

Lohys sheet iron and Hadfield's cast magnet steel, from which it will be seen that while the wrought iron is superior in permeability to the steel at densities of about 10,000 and under, beyond 16,000 the permeability of the steel becomes better than that of the iron, though not to any very noticeable extent.

A very useful way of showing the relative value of various brands of iron and steel for magnetic purposes is that of plotting, not the flux density produced by a given magnetomotive force, but the permeability (plotted vertically) against the flux density (plotted horizontally) and this has been done for brands of wrought iron and cast iron, in Fig. 133.

The student will always be amply repaid for a careful study of the shapes of the curves here given in Figs. 130 and 131, not only by a study of their shapes, but by committing to memory several pairs of correlated figures. For example, he will do well to bear in mind that ordinary wrought iron, such as Hopkinson tested, becomes saturated at about 16,000, and that to reach the point of saturation it requires a magnetising force of about 40 ampere-turns per centimetre of length of path, or an H of about 50. Other useful pairs of numbers that may be committed to memory are 16 ampere-turns per centimetre and a flux density of about 16,000 for both sheet iron and cast steel, and 12 ampere-turns for a density of 3,000 in cast iron.

The inspection of either of the sets of curves makes it abundantly clear that where weight of metal is not a matter of importance it will always pay to keep the induction density well below the saturation point, since after a magnetomotive force of about 5 ampere-turns per centimetre has been reached, double that value will only produce a 25 per cent. increase in the flux. Again, after the saturation point has been reached, a 100 per cent. increase in magnetomotive force is only accompanied by 10 per cent. in the magnetisation produced.

THE RISE OF CURRENT IN AN ELECTROMAGNET, AND THE ENERGY OF MAGNETISATION.

A coil of wire carrying a current produces of necessity a magnetomotive force unless special precautions are adopted to prevent this. Let us consider the absorption of energy in a conductor coiled, in the first instance, so as to generate a magnetomotive force; and, in the second instance, so as not to. A simple coil of wire will, as we have already seen, suffice for the first case. The total magnetising effect of the coil is really the sum of the magnetic effects of the current in each little element of the wire, the whole function of the coiling of the conductor being to so arrange these little effects that they are cumulative. Now if our coil contains, let us say, 100 feet of wire, and by coiling it in the simple fashion we can make the magnetic effects of all the elements add together, it is conceivable that we can also find a

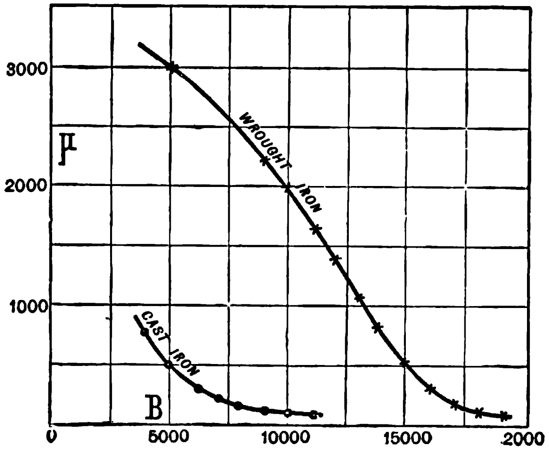


FIG. 133.—PERMEABILITY CURVES FOR WROUGHT IRON AND CAST IRON.

way of so winding the coil that half the magnetic effects *oppose* the other half. We may perform the addition, for example, by coiling 50 feet of the wire in one direction and the remaining 50 feet in the opposite direction. This might result in a fairly small total magnetic effect, but it is very doubtful whether the second 50 feet could be arranged really satisfactorily to neutralise the effect of the first 50. A far better way to arrange matters would be to take the middle point of the wire and to start winding with that, as is indicated in Fig. 134. If we now send current in at one end of the wire and let it traverse the winding and emerge at the other end, it is clear that in any pair of wires lying side by side, the current in one will be opposite in direction to the current in the other, and, as the two wires are so closely adjacent, each will to all intents and purposes completely neutralise the magnetic effect of the other. Further, if we take two coils containing equal lengths of wire, the one of which is wound simply or "inductively," and the other in the manner just indicated in Fig. 134, that is, non-inductively, we shall find, of course, that the resistance of the two coils is the same. Consequently to *maintain* a given current through them will require the same E.M.F. for each coil, and hence the same power, the whole of this power of course being spent in heat. The statement that both coils receive the same power is, however, only true as regards an absolutely steady current. It is not true of the two coils under all conceivable conditions.

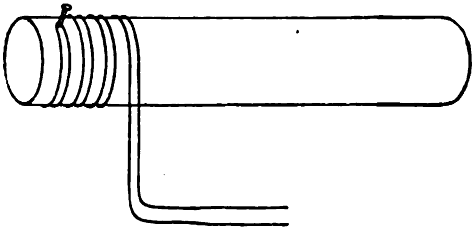


FIG. 134.—NON-INDUCTIVE METHOD OF WINDING.

If a steady E.M.F. be suddenly applied to the coil of an electromagnet the current in the coil will grow gradually from nothing up to its final value in a manner indicated by the curve in Fig. 135.

The final value to which the current attains is, of course, that given by Ohm's law, and represented numerically by the E.M.F. applied, divided by the resistance of the coil. The duration of the period of growth theoretically is infinite, for the current only approaches the value $\frac{E}{R}$ by imperceptible degrees, and requires an infinite time to actually attain that value. Practically, however, the period of growth may be regarded as the time occupied in reaching the top point marked in Fig. 135. The duration of this period varies with each individual coil, and depends upon a certain property of the coil which is known as its "co-efficient of self-induction." (*See* Sections V. and VI.) Helmholtz has given us an expression for the value of the current at any given instant *t* seconds,

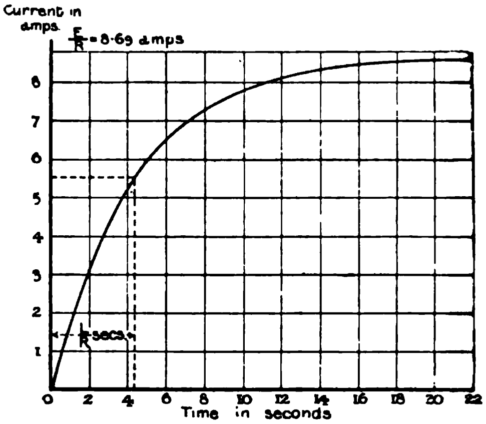


FIG. 135.—RISE OF CURRENT IN ELECTROMAGNET COIL.

counted from the time the E.M.F. was first applied. This expression is,

$$C_t = \frac{E}{R}\left(1 - e^{-\frac{Rt}{L}}\right)$$

in which L stands for the coefficient of self-induction of the circuit in henries and e is the base of napierian logarithms. If we apply this formula to a circuit in which the applied E.M.F. is 10 volts, the resistance = 1·151 ohms and L = 5 henries, we get the figures given in the following table for the current in the coil at successive intervals of time, counted from the instant the E.M.F. was first applied. These values are also represented in Fig. 135. Now this curve is very instructive, for no matter what the value of the E.M.F., or of the resistance, or of the self-induction, the general shape of this curve will be the same for any and every inductively wound coil or circuit, provided it is not one employed to magnetise *iron* as high as, or above, the "knee" of the iron curve. The reason why this curve will not apply to a coil so circumstanced is that the value of L will not remain constant for that circuit, but will fall off as the magnetic flux in the iron grows. So long, however, as the magnetism is not pushed to such a value that L changes appreciably, we may say that the curve in Fig. 135 will represent the rise of current for the coil of an electromagnet, as well as for any other inductive circuit. On looking at the expression given by Helmholtz we notice that the exponent of e involves the ratio R/L. Now, clearly, when Rt is equal to L the expression inside the bracket $\left(1 - e^{-\frac{Rt}{L}}\right)$ will become $\left(1 - \frac{1}{e}\right)$, and hence, at that number of seconds which will give Rt equal to L, the value of the current in the circuit is 0·634 of its ultimate strength.

Time in Seconds.	C. in Amperes.	Fraction of Total Value.
0·25	·435	0·056
0·5	·946	0·109
1·0	1·79	0·206
2·0	3·2	0·369
3·0	4·34	0·499
4·0	5·23	0·602
5·0	5·94	0·684
6·0	6·5	0·749
7·0	6·95	0·8
8·0	7·3	0·841
9·0	7·58	0·874
10·0	7·81	0·9
12·0	8·14	0·937
15·0	8·4	0·968
17·0	8·51	0·988
20·0	8·6	0·99

This value of the time is known as the "time constant" of the circuit, and the time constant of the circuit always expresses the number of seconds that will elapse between the instant of applying the E.M.F. and the attainment of a current 0·634 times the E/R value. It is at once apparent that this value of t is given by the ratio L/R, and hence this ratio is always referred to as the "time constant" of the circuit.

The curve is further very instructive if we consider its meaning as follows:—Since the voltage to maintain the current through the resistance of the coil is C × R, we may clearly regard the curve as giving the value of the voltage absorbed by the resistance at each instant. But the voltage applied to the terminals is constant from start to finish, and, therefore, until the steady period has been reached the whole applied voltage is clearly not absorbed in resistance. Upon what then is it expended?

It will be seen in the course of the next chapter that, when the magnetic flux is caused to increase in the interior of a coil of wire, the change in the number of lines threading the coil occasions an E.M.F. in the wires which constitute the coil; and further that the magnitude of this E.M.F.

is proportional to the time rate of the change. Mathematically expressed, this means to say that the E.M.F. set up is equal to dN/dt, where dN represents a change in the number of lines enclosed by one turn of the coil and dt the time which it takes to effect that change. If, then, we consider the electric circuit during the time that the induction changes through a very small amount we see that a change in current which produces a change in magnetism will be due, not merely to a change in the applied E.M.F. of the circuit, but also in part to the E.M.F. induced as just stated. We may not, therefore, simply write down that the change in current is simply proportional to the change in applied voltage, since the applied voltage is not the total E.M.F. in the circuit, and Ohm's law demands that we shall take full account of every E.M.F. Let us, then, adopt the following symbols and consider that they refer to a magnetising coil :—

a = the area of cross section of the coil.

S = the number of spirals of wire in the coil.

C = the current flowing.

E = the E.M.F. applied.

B = the flux density.

R = the resistance of the coil.

The symbols dC, dE, dB, dt, as usual, represent small changes in the above quantities which occur in correspondence with one another.

The E.M.F. that is induced by any change of magnetism will be in opposition to the applied E.M.F. producing the change (*see* next Chapter) so that the total net E.M.F. at work will be the applied E.M.F. minus the induced, and during a change in the magnetism we have, in order to satisfy Ohm's law, to write the expression for current :—

$$C = \frac{E - \frac{dN}{dt}}{R} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

and hence :—

$$E = CR + \frac{dN}{dt}$$

Here then we see that the applied E.M.F. is partly occupied (so to speak) in overcoming the resistance of the coil, and partly in overcoming the opposing E.M.F. represented by $\frac{dN}{dt}$. The former portion of the applied E.M.F. grows with time, and the latter decreases. These results are shown on the diagram in Fig. 136.

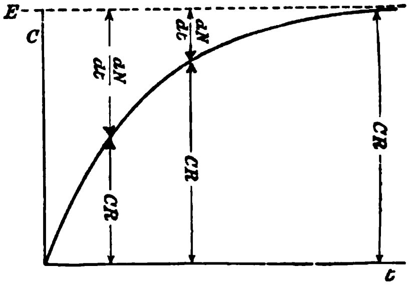


FIG. 136.—E.M.F. ABSORBED IN FIELD AND IN HEAT AT SUCCESSIVE INSTANTS OF TIME.

Now, whenever a current flows *against* an E.M.F. the circuit (or part) concerned in the back E.M.F. is *receiving* energy at a rate given by the product of current and back E.M.F. Here this energy is associated with a magnetic field and is stored in that field. The applied E.M.F is therefore partly connected with the heating of the coil (CR) and partly with the generation of a magnetic field $\left(\frac{dN}{dt}\right)$. The field having once been generated, however, demands no more energy, for when it is steady $\frac{dN}{dt} = 0$, and the whole applied E.M.F. is available for overcoming resistance, and the whole energy supplied heats the coil and does nothing else. The destruction of the field (when the current is stopped) liberates all the energy stored up, and this is, when thus liberated, returned to the circuit.

The effect of the energy demanded for the creation of a magnetic field, and of the return of that energy when the field is destroyed is precisely analagous to the effect of inertia when any mass has to be set in motion or to be stopped, and hence self-induction may fairly be regarded as the inertia of an electric circuit. It is entirely due to the presence of a self-inductive effect that a spark is formed when the circuit of an electromagnet is broken. At one time this effect was vaguely referred to as the extra current, but it is now well known, and the foregoing will have made it clear, that the destruction of the field belonging to the electromagnet is capable of restoring energy to the circuit at a sufficient rate to produce a spark of considerable strength when the circuit is broken. It cannot be too carefully insisted upon, that the presence of a spark in any part of a circuit when the curcuit is broken is due to self-induction, and that, therefore (except in the case of the most carefully wound non-inductive circuits), all ordinary circuits possess self-induction, and that it is this which occasions the spark when the current in them is suddenly stopped.

HYSTERESIS.

It is found that if iron be magnetised, and the magnetising forces be then gradually reduced, the iron will retain a great portion of its magnetism. In other words when the molecules have once been combed out all in one direction and then left to themselves they do not all readily return to their original grouped condition, and it is supposed that they are prevented from doing so chiefly by intermolecular friction, it being necessary to apply some force to enable them to rub past one another and so get back to their original positions. A simple but striking experiment illustrates thus. If a glass tube be filled with steel filings, not too tightly packed, and be then magnetised, it will behave like a bar magnet so long as it is carefully handled. A good shaking, however, which will thoroughly rearrange the filings, deprives it of all semblance to a permanent magnet, and it now behaves like a bar of unmagnetised steel. The force to overcome intermolecular friction in a bar of iron can be easily supplied by reversing the magnetising force which was first applied, and if a bar be subjected to a magnetising force which is slowly raised to a high value, then reduced slowly to nothing, and raised slowly from nothing to a high value in the reverse direction, the

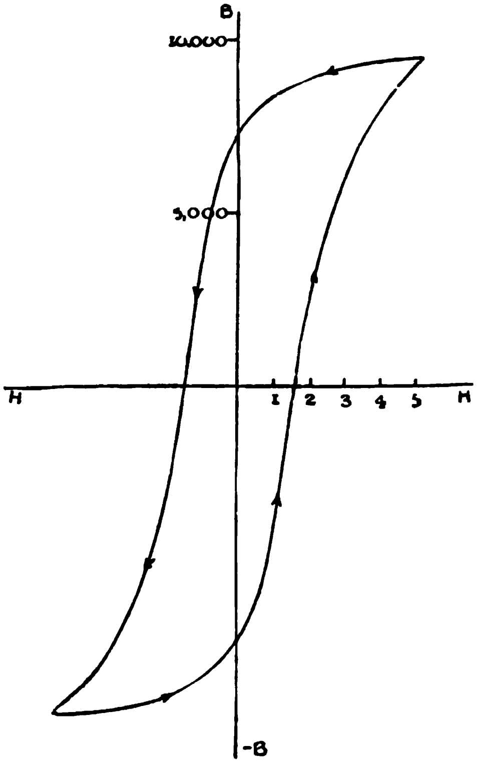


FIG. 137.—HYSTERESIS LOOP FOR WROUGHT IRON (EWING).

magnetisation of the iron follows the curves shown in Fig. 137.

It was pointed out by Professor Ewing and Professor Warburg, independently, that the curious curve in Fig. 137 has a definite and interesting physical meaning. The curve in question has been taken from Professor Ewing's paper before the Royal Society in 1885, and the arrow heads on the curve indicate the direction in which the magnetising process is being carried out. As the iron appears to lag behind the current in the descending branch of the curve Professor Ewing gave the name "hysteresis" to the phenomenon.

ENERGY OF HYSTERESIS.

If we consider the reflex effect of this behaviour of the iron (or, rather, of the magnetism connected with the iron) upon the coil through which the magnetising current flows, we shall arrive at the physical meaning above referred to as having been pointed out by Professors Ewing and Warburg.

In the case of air the curve connecting magnetisation and magnetising force is a straight line, and the reduction of the magnetising force is accompanied by an absolutely proportionate reduction of magnetisation, so that there is returned to the electrical circuit by the reduction of the magnetisation, an amount of energy precisely equal to that which had been expended in setting up magnetisation.

On the other hand, if the coil serves to produce a magnetic flux in any iron, the case is at once altered. If the current be what is known as an alternating current and continually carry the iron through a complete cycle of magnetic operations, following the curve in Fig. 137 then we shall find that the power demanded when a given current is flowing is greater for the coil which magnetises iron than for a coil having *no iron*. How then, are we to suppose that the presence of the iron, which, as we have seen, greatly facilitates the production of a magnetic field, should make a demand on the electrical circuit for additional power? The explanation is to be found in the peculiar shape of the curve. If the magnetism were to die down along the same curve as the magnetising force is removed, the work or energy which had been stored up in the magnetisation of the iron would be all returned to the circuit. We see, however, that the magnetism does not return along that curve, but along the upper line, as is indicated by the arrow head, and hence when the whole of the magnetising force has been removed the iron still remains magnetised, requiring, as we have already said, a reversal of the magnetising force to bring it back to the original condition from which it started.

Reverting to the symbols given above on page 200, it has been pointed out that the current in any inductive circuit at a given instant may be written as

$$C = \frac{E - \mathit{E}}{R} \quad . \; . \; . \; . \; . \; . \; (1)$$

Here E is the back induced E.M.F. and E that at the terminals of the circuit. In absolute units (*see* Section V.; also page 23) we can write

$$C = \frac{E - \frac{aN}{dt}}{R}$$

Or, if the current is to be expressed in amperes, and the E.M.F. in volts, and the resistance in ohms, we may write as follows:—[*]

$$C = \frac{E - \left(\frac{dB}{dt} \times a \times S \times 10^{-8}\right)}{R} \quad . \; . \; (2)$$

From this expression we can easily find

---

[*] The reader who has not already some acquaintance with the subject of the succeeding chapter, will do well to return to this point *after having read* Chapter IV.

the energy imparted during the time dt to the coil encircling the iron, for it must manifestly be the power multiplied by the time (*see* page 9), and will hence be equal to CEdt. We get the following expression by multiplying by C and dt.

$$C \times C \times dt =$$

$$\frac{E-\left(\frac{dB}{dt} \times a \times S \times 10^{-8}\right)}{R} \times C \times dt$$

$$C^2Rdt = ECdt - (dB \times a \times S \times 10^{-8})\ C$$

and by rearranging

$$ECdt = C^2Rdt + C\ a\ S\ 10^{-8}\, dB\ ;$$

but the magnetising force H may be written $\frac{4\pi\, CS}{10l}$ so that $C = \frac{10\, l\, H}{4\pi S}$ and by substituting this in the second term on the right hand side of the equation we get $EC\,dt = C^2Rdt + la\ H\ dB\, 10^{-7} \times \frac{1}{4\pi}$;

that is to say,

Energy given to coil in time dt =

$$C^2R\ dt + vol.\ of\ iron \times \frac{H\ dB}{4\pi \times 10^{7}},$$

Examination of this equation shows clearly that the first of the two expressions on the right-hand side is something with which we are already familiar, for it is the energy absorbed as heat by the copper in the coil. The second expression, however, is something different, and depends only on the volume of iron magnetised, on the ampere turns, and on the change in magnetisation, from which it is apparent that the remaining energy delivered to the coil is absorbed in the changes of magnetisation which occur in the iron. If this expression applies with certain definite values during the process of magnetising the iron, the values being taken from the lower line in the descending branch of the curve in Fig. 137, it will be seen that the total energy given out by the iron in the descending branch of the curve is less than the energy delivered to it during the ascending period, because the change in magnetisation is less. The consequence is that we can say the total energy *absorbed* in this operation is that which is delivered to the iron, and which the iron does not return to the circuit.

This is easily seen from above to be

$$\frac{10^{-7}}{4\pi}\int H\, aB \text{ watts}$$

per cubic centimetre for a given range of change in magnetisation. Between the limits shown in Fig. 137, this expression for the energy absorbed by the iron is also an expression representing the area of the total loop enclosed by the two branches of the curve. Hence if the curve be drawn to such a scale that the C.G.S. unit of magnetomotive force, namely, **H**, is represented by one centimetre and the C.G.S. unit of flux density (one line per square centimetre) is represented in the vertical scale by one centimetre, then the area of the loop in square centimetres will represent the energy absorbed per cubic centimetre of iron by the hysteresis measured in the C.G.S. unit, namely, in ergs.

In consequence of the above relation between the area of the hysteresis loop and the energy absorbed by the iron owing to hysteresis, the careful plotting of a hysteresis curve for any special brand of iron is exceedingly instructive and, indeed, it is very easy to make a comparison between samples of iron that may have been submitted and any standard brand which a manufacturer may have been in the habit of using, by simply comparing the areas of their hysteresis loops. The method of measuring the various quantities which enable the curves to be plotted is one which cannot be dealt with in this place, and the subject is therefore deferred until the latter end of the next section.

Hysteresis loops for various materials are shown in Fig. 138.

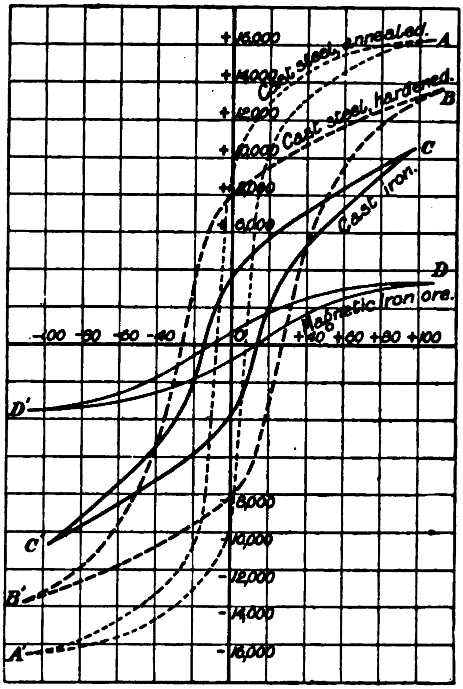


FIG. 138.—HYSTERESIS LOOPS FOR VARIOUS FERRIC MATERIALS.

SOLENOIDS.

We have already seen that a coil of wire with current in it acts substantially in the same way as a permanent magnet with reference to magnetic objects, such as iron compass needles, &c., external to itself. The solenoid, however, as a coil of this description is termed, gives you facility which a bar magnet does not. The solenoid is hollow, and if any useful magnetic effort can be found to exist inside the coil, there is nothing to prevent our turning that to good account. The iron filings on card in Fig. 121 show us that there are magnetic forces at work, and they show us that the inside of the coil is threaded by the lines of a magnetic field. If we place, therefore, a rod of iron inside the coil, the lines of the flux will presumably pass through the iron. Hence, if we bring such a rod slowly up to the coil from a distance, it will, during the period of its approach, form a path for a gradually increasing number of lines of flux. Now, iron traversed by lines of magnetic flux just constitutes what we call a magnet, and this way of producing a magnet, viz. by putting lines of force through it from another magnet, or from an electric magnet, used to be called magnetisation by induction. Our rod of iron as it approaches the coil is not, however, a magnet of constant strength, but, since the number of lines it carries is a gradually increasing one, its magnetic strength also increases as it approaches the coil. Arguing from the point of view that the solenoid is itself a magnet, we might conclude that the force between it and the approaching magnet would be a steadily increasing one, for we may on this supposition fairly consider the question of the force between the two as being that of a force between two magnets acting on one another, both of which increase in strength as they approach one another.

It is clear that the force must be one of attraction, at any rate while the rod is still outside the coil, since, by following out the lines of force, we see that if they are coming out at the end of the coil they must be going in at the end of the rod, hence the end of the coil and the end of the rod that are near to one another are surfaces of opposite polarity. If we test experimentally the truth of this argument concerning the force between the solenoid and the bar, we shall find that it is correct up to a certain point. So far we have made no particular assumption with regard to the length of the rod, although as a matter of fact this is a most important factor. If we take a rod of the same length as the coil exactly, we shall find that the rod certainly is pulled to the coil until it is entirely enclosed within the coil, but we shall not find that the force pulling it is a steadily increasing one ; it follows a curve such as those indicated in Fig. 142. We have just said that the length of the rod is an important factor in determining the way in which the pull varies ; by this was meant the length of the rod in comparison with the length of the coil. Not only, however, does the relation of length of rod to length of coil have an important effect, but the ratio of the length of the coil to its own diameter is also a factor not to be neglected.

The whole subject of the solenoid and its action upon a plunger such as the rod we have been considering is an extremely lengthy one, and has been dealt with in considerable detail by Professor S. P. Thompson and others. We shall not, therefore, in a work like the present, go into the subject very fully, but, since coils whose length is three or more times their own diameter are of very constant use in practical work, we shall discuss here some of the more important and interesting facts connected with such coils.

In the first place it is not at all difficult to see, upon a little consideration, why the pull on the plunger falls off soon after it has entered the coil. As we have said, if the rod is of the same length as the coil, it is pulled or sucked in until it is entirely enclosed within the coil, and for this reason the earlier investigators applied the term "sucking magnet" to such a coil and rod. If we carefully bear in mind what we have now defined as a north pole face and a south pole face, and apply these definitions to the coil and to the rod, we shall see that in Fig. 139 the right-hand end of the coil is a north pole face, and the left hand end a south ; as the plunger enters, the lines traverse it likewise from left to right, with the result that the left-hand end of the rod is a south pole, and the right-hand end a north pole—or if not the *end*, at least there is a north polar surface like a short sleeve over that part of the rod. When the end of the rod has entered the coil, this method of pull action appears to break down, since we no longer can deal with surfaces, such as the end of the coil and the end of the rod, which may be considered to attract one another in a simple manner. What was, and is, the south end of the rod is now inside the coil, and if we continue the application of the pull action argument to the case, we must suppose that this end of the rod is now being forced towards the south end of the coil—that is, is being forced against an action of repulsion between two similar poles. A similar statement might be made regarding the other end.

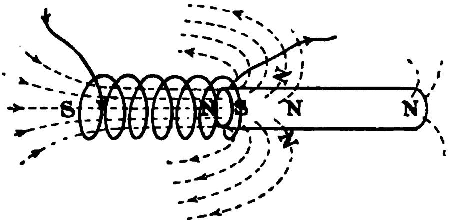


FIG. 139.—PATH OF FLUX AND POLARITY OF SURFACES WHEN PLUNGER IS ENTERING COIL.

A simpler way of considering what will happen as soon as the end of the rod has entered the coil is to have recourse to what is one of the most important of the laws of magnetics. According to this law, which was first stated by Professor S. P. Thompson, the force on any piece of iron in a magnetic field in air is such as will tend to move the iron so as to reduce the reluctance of the path of the field. This needs more explanation. We have stated an Ohm's law for magnetism just above, and in it we find that magnetic flux is numerically equal to magnetomotive force divided by magnetic reluctance. We have also pointed out that iron is a very far better conductor for magnetism than air. Now, when there is no iron present the path of the lines due to the solenoid is entirely in the air, and they follow the course indicated at Fig. 140; whereas, as soon as the iron enters, the path of the flux, now partially in air and partially in iron, is changed and follows a course pretty much as is indicated at Fig. 141. If we now consider what it must be when the iron is entirely inside the coil, we shall find that at least half its path is very greatly improved by the presence of the iron, for whereas before the whole of the flux traversing the inside of the coil had before to be carried by air, it now has a path through iron, which, if the iron be not saturated, is at least 300 times as good, and may be much better still. Hence, if, as we have said before, iron tends to move so as to afford the best possible path for a magnetic flux, it is clear that the iron must go on moving until it reaches a position of being entirely enclosed. We have still not explained why this force pulling the iron into the coil falls off after the iron has entered. This is to be explained in the following way. The magnitude of the force tending to move a piece of iron from one part of a magnetic field to another depends simply upon the magnitude of the improvement in the magnetic conductivity which will be made by the movement of the iron from the one position to the other.

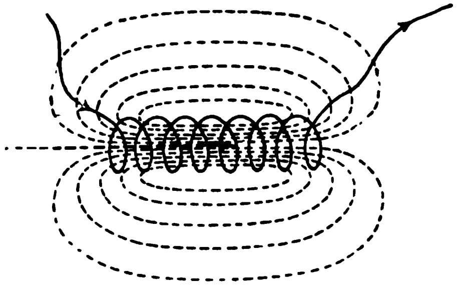


FIG. 140.—PATH OF FLUX DUE TO SOLENOID.

Now, so long as the iron in our present case has only partly entered the coil, every little further movement of the iron is accompanied by a very great improvement in the magnetic path, until the end of it has got about half way through the coil. After this point has been reached, however, the further movement of the iron does not so greatly improve the magnetic path, and hence, owing to the falling off of the *rate of improvement* with the continued movement of the iron, there is a falling oft in the magnitude of the force which tends to produce the movement. A very interesting way of applying the theory of pull action is by remembering that a surface is an imaginary plane separating two dissimilar substances in contact, and we can, by supposing this surface to be a slab of some thickness, consider that side of it which the lines of force enter as a south pole, and the other side, of course, a north pole.

We will next consider the case of a coil and rod in which the rod is longer than the coil by say 25 per cent. Here we find by experiment that the rod will be pulled into, and through the coil until the entering end has emerged from the opposite end of the coil; and that the pull is even then continued until the end that first entered the coil projects as far from that end, as does the trailing

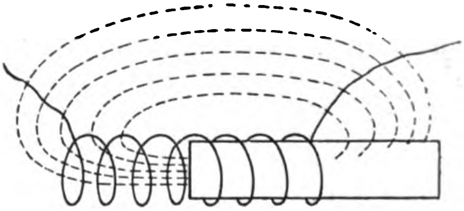


FIG. 141.—PATH OF FLUX WHEN PLUNGER HAS ENTERED COIL.

end of the rod from its end. In other words, the rod is pulled in until its own centre point is just in the middle of the length of the coil. Our former explanation suffices equally well for this case, for until the entering end of the rod has protruded from the back end of the coil the magnetic circuit is not quite so good as it might be. It is not quite so good because a length of iron is left protruding from one end of the coil and the lines of force entering at that end must, if they are to go through iron, take a slightly longer path through air. If the iron moves, however, until it projects equally at each end of the coil, the magnetic path is slightly improved and is, indeed, then at the very best that it can possibly be with that coil and that rod.

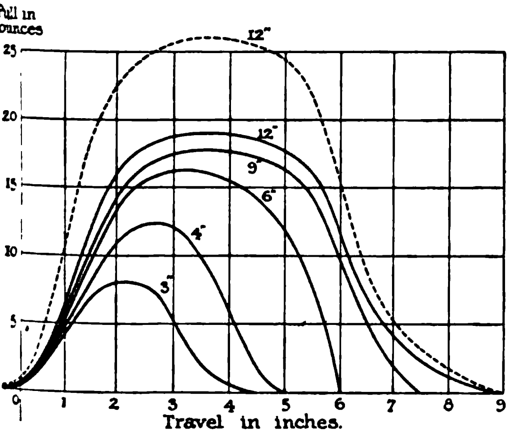


FIG. 142.—CURVES OF PULL OF SOLENOID ON PLUNGERS OF VARIOUS LENGTHS. COIL 6" LONG; 640 TURNS; CURRENT 7·5 AMPS.; DOTTED CURVE 10 AMPS.

From providing the flux that is inside the coil with an iron path it is a simple and obvious step to provide it also with an iron path external to the coil. We may at once do this by bringing up a second rod after we have first introduced one into the cavity of the coil. We are still, however, short of the best possible arrangement, since the flux goes down the outside of the coil on all sides, and in order to provide the whole of it with an iron path instead of air we should surround the coil entirely with iron rods This, of course, is clumsy, and at once leads to enclosing the coil in a tube of iron, when we arrive at an arrangement such as is indicated in Fig. 143. There still remain the two ends at which a path for the flux may be afforded from the rod to the tube by means of two discs of iron.

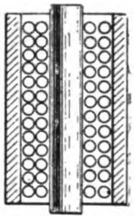


FIG. 143.

We have thus arrived at a form of electro-magnet in which the path for the magnetic lines is composed entirely of iron. Such a form is quite unsuitable, and except under most exceptional conditions absolutely useless for any purpose where forces of magnetic attraction or repulsion are required to be brought into play It will be remembered that these forces, that is, those of attraction and repulsion, only occur when the magnetic path can be improved by the relative movement of coil and iron. The forces then appear to act between what we called pole faces; in the case of an iron magnet of any kind these were surfaces of iron at which lines of force passed from iron to air or *vice versa.*

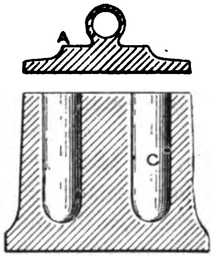


FIG. 144.—"POT" ELECTROMAGNET.

In our present "ironclad" form of magnet no such pole surfaces are present, for if the two end discs are carefully fitted, so that each touches one end of the rod and the edge of tube, it is clear that the flux passes from rod to tube without traversing air. If, however, we shorten or lengthen either the core or the jacket (as we will now call the rod and tube respectively), we at once reintroduce an air gap into the path of the flux, and find, of course, two pole surfaces of opposite polarity. Between these there must be a force of attraction. We have, in point of fact, arrived by this means at one of the most powerful forms of electromagnet that can be devised; most powerful, that is, for its size and weight. It is not altogether the most convenient form for all purposes, but is extremely useful where a very compact light magnet is required for the purpose of holding on only. It is commonly known as a "pot magnet," and the disc which fits the core and jacket, leaving no air gap, is called a yoke; while the disc at the end, where there is a small air gap left, may be called the armature. In practice, magnets of this form are commonly made up from a casting of the shape shown in section at Fig. 144; or if the magnet is to be particularly light and strong it is made up from wrought iron, the pieces being screwed together. The coil is, of course, placed in the annular space marked C, and is usually wound on a bobbin and slipped into place. The armature shown at A is generally made so as to carefully fit both on to the core and jacket, so that when in position there is no air gap, there being, just before the armature comes into contact with the core and jacket, four pole surfaces, between each pair of which there is a powerful force. These four pole surfaces are the core and the surface of the disc just opposite it, and the top edge of the jacket with the surface of the disc just opposite that.

The two forms in Fig. 148, are drawn carefully to scale, so as to show the relative size of the two for equal strength when made of cast iron and cast steel respectively. They are both intended to receive current at the same pressure.

Such magnets as these, while having extremely great force of attraction for their armatures when the latter are practically in contact with the poles, have an exceedingly limited range of action. The poles of the magnet are, of course, the end of the core and the circumjacent edge of the jacket, and these are necessarily close together. The result of this is that when the armature is removed the lines of force which come out of the core find a short and fairly easy path radially in every direction from the core to the jacket, and so do not tend to leak away much by paths traversing the surrounding space. Hence the bringing of the armature to a position a short distance from the poles does not tend materially to improve the path of the magnetic flux, since any flux which has to get to the armature has to pass up through air from the core into the disc, then down again into the jacket, instead of going radially along a practically straight course from core to jacket. Until, therefore, the armature reaches a position such that the path of a line through air from core to armature and back from armature to jacket is comparable with the straight path radially from core to jacket, there will be little appreciable force upon the armature. When, however, the armature does reach such a position, any further movement towards the poles is accompanied by a rapid and notable improvement in the magnetic circuit, and consequently by a big force of attraction. The consideration in this way of the improvement of the magnetic path by the presence of an armature, or by the addition of iron to any part of an electromagnet would, if carefully gone into, often save would-be inventors of special forms of electromagnets much disappointment and failure. This is, indeed, the key to the whole subject of electromagnet design, and in this view the very great importance of what we have called Ohm's law for magnetism will be readily appreciated. While, however, the simple consideration of the magnitude of the improvement caused by the addition of iron, or by the presence of an armature, is a guide to the design of an electromagnet, it does not convey very detailed information applicable to the whole range of action of such a magnet. The pot magnet, for example, just described, while extremely powerful, had, as we saw, a very limited range of action, due to the fact that as soon as the armature had passed to such a distance from the poles as was comparable with half the distance between them, its presence had little effect on the magnetic path. If we are to produce an electromagnet of greater range of action, it must be one in which the distance between the poles is such, or the direction of the magnetic flux is so arranged, that the presence of an iron armature at a considerable distance from the poles has a relatively large effect on the goodness of the magnetic path. Further, besides a long range of action, it is very desirable in some cases to devise electromagnets whose pull on their armature shall not greatly vary throughout a considerable range, and the condition to be aimed at in such designs is that, throughout the desired range, a given movement of the armature shall produce as nearly as possible the same degree of improvement in the magnetic path. In other words, the force tending to move the armature from one place to another depends upon the rate of improvement of the path. In order to illustrate these principles, one or two magnets of varying design will be considered in detail, and their action and attainment of the desired object explained.

THE PULL OF A MAGNET.

Up to the present we have only spoken of the relative strength of magnetic pull and of the points to be attended to in general design with the view to attaining a desired object. We find need, however, to know what is the real magnitude of the force with which a magnet holds on to its armature when the latter is actually in contact with the poles. This was the subject at one time of very much investigation, which was both painfully laborious and, in view of the then existing knowledge, scientifically carried out. Many attempts were made, for example, to find an expression for the strength of a permanent steel magnet in terms of its weight or dimensions. An interesting account of these investigations, and of the results which were deduced, is to be found in Professor S. P. Thompson's book on "The Electro Magnet." The properties of premanent steel magnets are of very little value to us in this direction, although such information as is likely to be of practical use will be given after we have considered electromagnets a little further.

THE WINDING OF ELECTROMAGNETS.

In designing an electromagnet for any specific purpose, the first things that we have to consider are, obviously the strength of the magnetic field to be produced and the area over which that field is to obtain. This amounts, of course, to knowing the total number of lines of force or total flux that we have to produce. Having determined this, the necessity is then laid on us of deciding in what way we are going to produce this amount of flux. It has been shown (*see* page 194) that to produce a given flux through a given magnetic circuit, we have a variety of ways at our disposal, since the necessary magnetomotive force expressed in ampere-turns may be obtained by any combination of amperes and turns that will give the necessary product. As a rule, however, the problem does not present itself to us in quite so simple a fashion; since the magnetic circuit is not given, we generally know nothing of its length nor of its area of cross section, but merely the total flux and the area of the pole faces. On the other hand, even when these are known to us, we have not unlimited licence in the matter of ampere-turns, because we are generally informed of the character of the source from which our electrical energy is to be derived, and hence also of either the total current at our disposal or of the total pressure. As a rule, therefore, the quantities which we are left to determine by design are the length of the magnetic circuit and the size and length of wire to be employed. The processes by which we finally arrive at a satisfactory design will be most clearly followed, and the reasons for their adoption best appreciated, if we first make an attempt to design a magnet for a given purpose by unsatisfactory methods, which bring us into encounter with the difficulties which the proper methods avoid. Let us set ourselves the problem of designing an electromagnet which is to be capable of supporting a load of two tons when its armature is in contact with the pole faces. As regards the electrical supply, all we know is, let us say, that the pressure at which we may take current is 500 volts. In the first place, then, we make use of Clark Maxwell's result that the pull of a magnet in dynes is given by the expression—

$$\text{Pull} = \frac{\mathbf{B}^2 A}{8\pi} \text{ dynes.}$$

This, however, is in dynes, and we wish to reduce it to pounds. There are 981 dynes to the gramme, and 453·6 grammes to the pound. Hence—

Pull in pounds =

$$\frac{\mathbf{B}^2 A}{8\pi \times 981 \times 453{\cdot}6} = 8{\cdot}95\, \mathbf{B}^2 A \times 10^{-8}$$

We now find we have to choose such values for **B** and A that **B**² A shall have the product desired. Clearly we are open to make A anything we like, since we are not given any definite pole face: having assumed A in square centimetres we must provide a sufficient magnetomotive force to bring **B** up to the value such that

$$\mathbf{B}^2 = \frac{4480 \times 10^8}{A \times 8{\cdot}95}$$

This, of course, supposes that no conditions have been laid upon us as to the total dimensions of our magnet; that is to say, we have not been told that the magnet itself shall be less than any definite weight, nor are we limited as to the space it shall occupy. There is, however, a consideration which we do well to impose upon ourselves, and to take into account at this stage, since if we neglect it now it may lead to our having to modify the design very much after it is supposed to have been completed. Reference to the curve given on page 197 shows that up to a flux density of about 16,000 the permeability of wrought iron does not fall off very rapidly. In other words, for a given expenditure of magnetomotive force we get a good return in the shape of field strength. If, however, we push the flux density in the iron beyond that point, we do not, so to speak, get as much value for our money, for if we double the magnetomotive force requisite to produce a **B** of 18,000, we do not get anything like 36,000, but merely a paltry increase of about ten per cent. Clearly, then, it will be economical in magnetomotive force if we restrict ourselves to a flux density not exceeding about 18,000; and indeed, we shall do well, possibly, as we are not limited for space or weight, to keep it down as low as 16,000. An economy in magnetomotive force means, of course, an economy in ampere turns, and therefore in wire for winding the magnet or in current to be taken to excite it. On the other hand, were we given a definite flux to be produced, a diminution in the flux density, which is the necessary accompaniment of reduced magnetomotive force, would mean an increase in the cross-sectional area of the iron, so that any steps which we take to economise magnetomotive force are bound to result in the opposite of economy in some other direction, say in additional expenditure on iron. Iron is, however, a cheap material, and we may to some extent afford to design for much iron if it is going to effect an economy for us in copper and current. In all matters of design, however, whether it be for electromagnets, or houses, or what not, the function of the designer is always to make a compromise between conflicting conditions. If he effects economy in one direction, he is sure to be involved in greater outlay in another if the conditions imposed are strictly fulfilled, and the business of the designer is invariably to try and adjust his design to secure the best total economy; so that his retrenchments in one direction should not be overbalanced by, but should overbalance, his additional expenditure in another direction. In our case we will retrench, let us say, in copper and in current, but only so far as will not cause an overbalancing expenditure in iron. The effect on the area of iron at the poles produced by varying the value of B is shown by the curve, Fig. 145; but although this tells us the area of cross-section of the magnet poles, the information it gives is insufficient, for the following causes: In the first place, we are not bound to make the sectional area of our magnet the same throughout. We may, if we please, and if we can, make the flux density

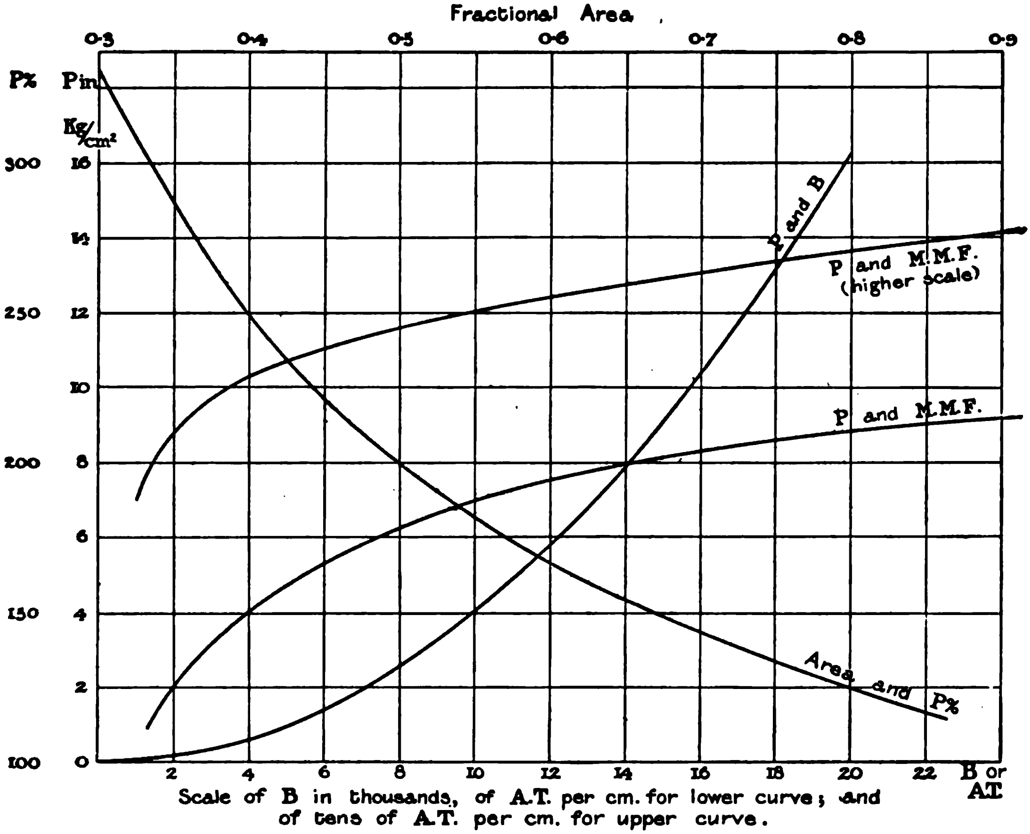


FIG. 145.—CURVES CONNECTING PULL WITH B AND A.T. PER CENTIMETRE FOR WROUGHT IRON.

at the pole faces, where the pull is actually exerted, high by crowding lines through a small area, while we keep the flux density in the rest of the magnetic circuit comparatively low, in order to effect economy in magnetomotive force. Further, a reduction in the flux density (assuming that we have a fixed total flux to produce) will mean an increase in the cross-sectional area of the limbs of the magnet, but will permit us, by reason of the economy in magnetomotive force, to keep the length of the limbs short. The net result is that while the area is increased the length is diminished, and hence the effect (on the total mass of iron) of changes in flux density is not very obvious. In order to present them in as concise a form as possible, the author has embodied them in the annexed curves, Fig. 145.

Without referring further to these at present, we will proceed with the design of our magnet on the assumption that we shall effect the most economical design by taking a flux density of 15,000. We will choose for our material the mild steel which is now so very largely employed for dynamo castings. The curves for this are given on page 191, and we see that at 15,000 it has a permeability of about 640. This will mean, as we find by reference to our curve (Fig. 145), a pull of 20·1 lbs. per square centimetre, and that we must therefore have an area of 223 sq. cm. We will now first continue on the assumption that our magnet is to have no pole pieces, that is to say, that the cross-sectional area of the limbs is to be the same as the area of the pole faces, and as we have not yet decided what the shape of the cross-section shall be, we will now take it to be circular. We choose a circular cross-section in preference to a rectangular or square one, because it is the shape which gives us the smallest possible perimeter for a given area, and as we do not expect to have much trouble in dissipating the heat produced in the exciting of the coils, we are not concerned to give them a very large area exposed to the air.

The sectional area thus arrived at (viz. 223 sq. cm. or 34·6 sq. in.) is the area of adhering pole face, and as there are two poles over which the load is distributed, each pole must have a face area of half this. This will mean a diameter of 11·9 cm. or say 12 cm., and we may now make a rough sketch of our magnet. We will assume that it looks something like Fig. 146, and as we presumably know nothing of the amount of wire wanted, we leave 18 cm. between the limbs. By making the armature and yoke rectangular, and of flattened cross-section (*i.e.* not square), we can slightly reduce the length of the magnetic path. If we give it a rectangular section 12 × 9·5, it will be equal in area to the pole faces, and this is what we have adopted in the sketch. Of the length of the limbs we know nothing at present except that they must be long enough to receive the windings. It is of no use to make them longer, for the longer they are the greater the reluctance interposed in the path of the flux, and hence the greater the requisite magnetomotive force.

As a matter of fact, if we are not restricted in the current to be taken from the mains, we may probably cut our magnet limbs down in length to about half an inch. The only thing which makes us give the limbs any appreciable length is the fact that the magnet limbs are connected at two extremities by a yoke and at the other two by the armature which holds the load, and since the whole of the magnetic flux has to pass through the reluctance of this yoke and armature, some magnetomotive force must be provided to maintain them excited. The limbs, then, must have some length in which to accommodate the coils. Let us now either ourselves impose a reasonable limit on the current to be taken from the mains, or obtain such a limit from our supposed customer. We will suppose that he has limited us to a current of 1·5 amperes. It is as well to point out here that there are considerations in special cases quite apart from the mere matter of past experience in design. The magnet we have before us is presumably designed for a certain duty. It may be intended, for example, to hold on to the side of a vessel, an iron ship, to serve as a back for a drill or riveting machine. If so, it is undoubtedly replacing some other device which has hitherto been in use for the same purpose. In this case, therefore, it becomes a question for the purchaser whether or no it will be to his advantage financially to purchase and use this electromagnetic device in preference to the devices which have hitherto been at his disposal. This at once brings a double consideration into view. The cost to him of employing the electromagnetic device is clearly twofold. In the first place, there is the yearly interest on the money which he spends on the purchase, together with any cost of upkeep; and in the second place there is the yearly cost to him of the current he takes to excite the magnet. These amounts have to be compared with the cost to him every year of rigging up the devices he has hitherto employed, and by this comparison he can tell whether or no it will pay him to go in for the electromagnetic device. He may also have to consider whether the electromagnetic device, even if the annual cost of it to him is greater, will not enable him to effect his work with greater rapidity, and so still be advantageous to him from a commercial standpoint. Of this he is probably in a good position to judge; and if he can then estimate what is to him the maximum permissible annual cost of an electromagnetic device, and communicate that figure to the designer, the designer should be able to give a definite pronouncement. Apart from the compromise between copper and current on the one hand, and iron on the other, of which we spoke just now, the designer has, when in possession of the above information, a further compromise to make. It will lie between copper and current. If he attempts to economise in current by increasing the number of turns he puts on, then his cost of copper and labour of making will go up; and if, on the other hand, he attempts to cut down the amount of copper, the yearly charges for current will go up. We will not suppose, however, in the present case, that we are given such a limitation of maximum annual cost, but will revert to the condition stated above, namely, one of a definite current at a definite voltage.

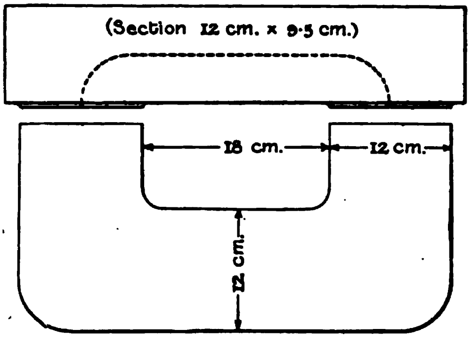


FIG. 146.—SKETCH OF IRON PORTION OF HOLDING-ON MAGNET.

Supposing our sketch (Fig. 146) to represent a trial design for the magnet body, we have to calculate the amount of excitation required. The flux density has been fixed at 15,000; at this flux density the material has a permeability $\mu = 650$. Hence $H = 23{\cdot}1$, and the ampere-turns needed will be $A\,T = \dfrac{23{\cdot}1}{\dfrac{4\,\pi}{10}} = 18{\cdot}4$ per cm. of path traversed by the flux. Now all the flux does not traverse the same path, and we have to estimate a mean path from our sketch. A fair mean path through the armature has been indicated by a dotted line. The curved portion may be taken to be a quadrant of a circle of 4 cm. radius, or 6·28 cm.; then there is a straight piece of 2 cm. before it emerges from under the pole edge. There are 18 cm. between the poles, and a piece under the other pole similar to the one just estimated. The two raised portions cast on the armature are provided to allow of their being planed and surfaced to a fairly true surface. They are given as 0·5 cm. high; hence the total path in the armature is 18 + (2 × 8·28) + (2 × 0·5) = 35·56 cm. The path in the yoke is similar to that in the armature, except for the projections last mentioned. Armature and yoke together, therefore, provide a path 70·12 cm., or say 70 cm. long. The path is of uniform cross section, or practically so, the armature and yoke having been purposely dimensioned to that end. The 70 cm. of path will therefore require 70 × 18·4 = 1,290 ampere turns altogether, or a winding of 860 turns carrying the 1·5 amperes determined upon.

On the assumption now that this is the current to be employed, we have little difficulty in selecting at least a minimum size of wire if we know whether the magnet is to be in continuous or intermittent use. We will assume that it is to be in continuous use, and in that case we must not employ a greater current density than about 450 amperes per square centimetre (3,000 amperes per square inch), which density will involve a wire of 0·0575 cm. (·0226 ins.) in diameter. It should have a double covering of cotton, which will increase the space occupied by each turn to 0·09 cm. (·0352 ins.) Now we have to wind 860 turns of this wire on the limbs of the magnet, and if our coils are wound in a single layer direct on the iron, they would occupy a length of 77·5 cm., or 30·5 ins. We are, however, by no means limited to the employment of a single layer, but may, if we please, wind the wire on several layers deep. We shall find that in order to prevent undue heating it is not well to wind the coils more than 12 mm. (say half-an-inch) deep, because the only surface by which heat can readily escape is the outer surface of the coils, and if we increase the number of layers beyond this, the whole of the heating, practically, from the innermost coils has to escape by passing through the outer layers to the air, and hence the temperature of the innermost layers is likely to rise to at least an unsatisfactory, if not a dangerous, value. We will err on the safe side and wind on nine layers, which will give a depth of about 8 mm. The total length of coil required will be that occupied by $\frac{1}{9}$ × 860, or say 96 turns. These can be disposed half on one limb and half on the other. In this way each limb must provide space for a coil 48 × ·09 = 4·3 cm., say 4·4 For convenience in winding, the coils will be wound on bobbins, and we proceed to sketch out a bobbin that appears to be suitable. It shall be of 4 mm. micanite, and the total length of limb to accommodate the bobbin will thus be 4·4 + ·8 = 5·2 cm. Allowing for means of fixing the bobbin we shall need at least 6·5 cm. These 6·5 cm. of iron in each limb have also to be magnetised. Their area and permeability is the same as that of the rest of the circuit, and we shall thus want 13 × 18·4 = 238 more ampere-turns, involving 159 additional turns. Half of these can be disposed on each bobbin, which will thus have to carry the former 430 + half the 159 just estimated, making a total of, say, 510. We have room to make our bobbin 2 mm. longer, and can thus put 50 turns per layer and 10 layers, bringing our winding depth up to 10 × 0·09 = about 1 cm. = 0·4 in.

We do not yet know what current will pass through these coils if connected to the 500 volt supply. We need to know their resistance. As we proceed to estimate this the first thing that strikes us is, of course, that the length of wire in any one layer of winding is different from that in any other, since the diameter of the coil increases as the layers get nearer the surface. We may, however, make a very rapid calculation of the resistance of a coil by considering the mean length of a turn and then multiplying by the total number of turns. In the present case the mean length of a turn is $\pi\,(12 + {\cdot}4 + 1)$ cm. $= 42{\cdot}1$ cm., and as there are twice 510 turns whose area is $2{\cdot}6 \times 10^{-3}$ cm.^{2}, they will have (*see* pages 13 and 15) a resistance at a temperature of about 32° Fahreneit, or zero Centigrade, of

$$\frac{2 \times 510 \times 42{\cdot}1 \times 1{\cdot}6 \times 10^{-6}}{2{\cdot}6 \times 10^{-3}} \text{ ohms,}$$

or, 26·45 ohms.

WINDING FOR A GIVEN VOLTAGE AND M.M.F.

If the voltage of supply and the required magnetomotive force are both given to us, there is a very simple consideration which quickly leads us to a satisfactory decision as to the size of wire to be employed. The consideration in question is that of the resistance of the mean turn of the coil. If, for example, we are required to provide a magnetomotive force of 5,000 ampere-turns from a supply at 100 volts, and are not given any other restriction, we may wind a number of coils all of different sizes and containing wire of different sizes, but all of which give us the required magnetomotive force, provided only that the resistance of a mean turn is the same for each coil. The determination of what this resistance should be is excessively simple, for let us consider the extreme case in which we have only one turn. If we have only one turn it is quite clear that we must have 5,000 amperes; hence the resistance of our mean turn must be one-fiftieth of an ohm. If now we put on two such turns we shall double the resistance and halve the current; but that halved current will pass through double the turns, and we shall hence have the same magnetomotive force as before. Or again, if we put on ten turns each of this resistance, our current will be reduced to 500 amperes, since the resistance has been increased to ·2, but these 500 amperes will flow through ten turns and still have 5,000 ampere turns. Hence it is clear that, provided we keep the resistance of the average turn (or the average resistance of a turn) to the required value, it is quite immaterial, from a magnetic standpoint, how we wind our coil. From the electrical standpoint it is also immaterial, provided we pay attention to one thing, viz., the heating of the wire. Provided we give the wire sufficient section to carry the current which will flow, without fusing or overheating it, it does not matter what wire we use. It may matter from the point of view of space occupied, but not from the purely electrical point of view. The consideration which in such cases does really lead us to a definite conclusion is usually either one of maximum current to be employed in addition to the definite voltage of supply, or else it is a question of balancing the cost of the copper and labour of winding against the consumption of energy in exciting. There is, however, a complication in some cases, introduced by the fact that in a given coil filled with wire, the thickness of the covering on the wire bears in the case of very fine wires a much larger proportion to the diameter of the wire than in the case of heavier wires. This means that, of the total volume occupied by the winding, the proportion of the volume occupied by cotton to that occupied by copper increases as finer wire is used. In the case too of coils which are wound to stand exceptionally high voltages, insulation has to be introduced other than the cotton covering on the wire itself, and the thickness of this insulation is usually constant, and it is introduced after a definite number of layers without it have been wound. Thus it may be introduced at every second, third or fifth layer, and so on; and in the event of a very fine wire being used, the frequency with which this insulation is introduced increases, and there is, therefore, a gain in the proportion which the space it occupies bears to the total volume of the coil.

If we assume that the coil just calculated will warm up to about 50° Centigrade in use, the result must be corrected to the following value:—

$$26{\cdot}45 \times 1\,(1 + 50 \times 0{\cdot}00388) = 31{\cdot}6 \text{ ohms.}$$

If we connect these coils directly across the 500 volt mains they will pass a current of

$$\frac{500}{31{\cdot}6} = 15{\cdot}8 \text{ amperes.}$$

which is ten times as much as we want. Clearly then we must either insert some additional resistance in series with the coils, or wind them with different wire. The former method would be easy to carry out, but would be exceedingly wasteful. It would mean adding an extra resistance such as would bring the total resistance across the mains up to

$$\frac{500}{1{\cdot}5} = 333 \text{ ohms.}$$

The coils afford 32 of this, leaving 301 to be added. Of the total resistance then, only one-eleventh would be usefully employed; or, to put it in other and better words, only one-eleventh of the applied voltage would be usefully employed. That this is so, is readily seen by remembering that the voltage at work (see page 30) across any conductor is equal to the product of the current and resistance, so that the voltage at work across our coils is only one-tenth of that across the external resistance.

If we re-wind the coils it must be done with a view to giving them higher resistance. Obviously we shall not do this by using wire of higher resistivity but by using smaller wire, also of copper.

It is interesting here to note how, if we neglect this question of the effect of insulation, the resistance of a bobbin of wire will vary as that bobbin is filled with wire of varying diameter, assuming that we always fill it to the same depth. If we call the length of the bobbin shown in Fig. 147 a inches between the cheeks, and the radial depth of the cheek b inches, the diameter of the covered wire d inches, it is clear that the number of turns per layer will be $\frac{a}{d}$, while the number of layers possible will be $\frac{b}{d}$; hence the total number of turns will be given by the expression $\frac{a\,b.}{d^2}$ Now the length of a mean turn is the same if the bobbin is filled, no matter what wire is employed, and if c is the diameter of the empty bobbin, this length will be $\pi\ (c + b)$; the total length of the wire employed, therefore, will be $\frac{a\,b}{d^2}\ \pi\ (c + b)$. Now the resistance of the filled bobbin will depend not only upon this length but also upon the cross-sectional area of the wire employed. The cross-sectional area of the wire is, of course, $\frac{\pi}{4}\,d^2$. Hence the total resistance of the bobbin will be

$$\frac{a \times b}{d^2} \times \pi\ (c + b) \times \frac{\sigma}{\pi/4\ d^2}$$

where σ is the resistance of an inch cube in ohms.

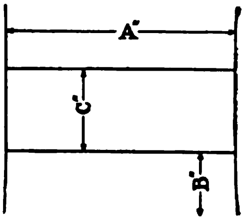


FIG. 147.

We thus get the rather surprising result that, apart from the question of the thickness of insulation, the resistance of our

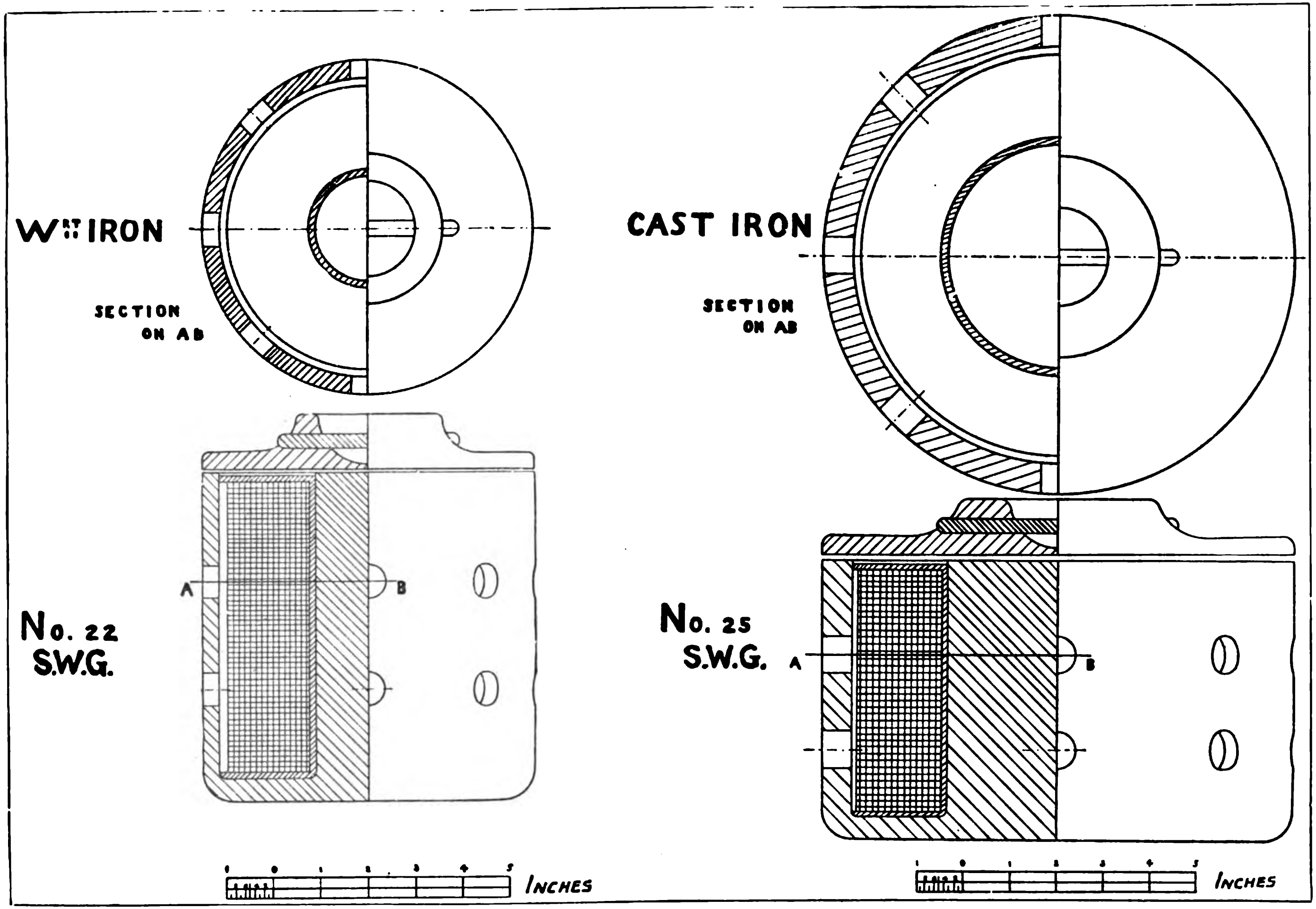


FIG. 148.—COMPARISON BETWEEN A WROUGHT IRON AND A CAST IRON MAGNET, EACH TO HOLD ON WITH A PULL OF HALF A TON, AND TO BE SUPPLIED AT 100 VOLTS.

bobbin will vary inversely as the fourth power of the diameter of wire employed to fill it. It must be clearly borne in mind, however, that the conditions of this investigation are simply the filling of a bobbin of fixed dimensions, a condition entirely different from that of providing a bobbin the resistance of whose mean turn is constant. The resistance of the mean turn of the bobbin of fixed dimensions clearly varies with every change in the diameter of the wire, the length only of the mean turn remaining constant.

THE ACTION OF AN ELECTRIC BELL.

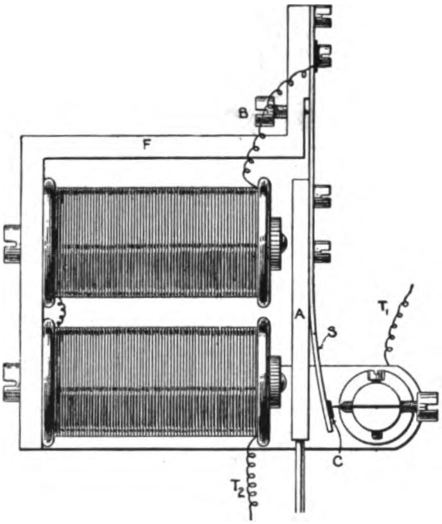


FIG. 149. — ELECTRIC TREMBLING BELL MECHANISM: A, ARMATURE; B, ADJUSTING SCREW; C, VIBRATING CONTACT; F, FRAME; S, SPRING; T_1 AND T_2, TERMINAL WIRES.

Quite one of the commonest and most commonly misunderstood applications of electromagnetism is its employment in the mechanism of a trembling electric bell. In an electric bell of this type there is provided an electromagnet, usually of horseshoe shape, provided with an armature which is carried by a flat spring to which it is attached by one end. The other end of this spring is usually fixed to an iron frame, which also serves to carry the horseshoe electromagnet. The spring is so set that it normally holds the armature away from the poles of the electromagnet. In bells of the ordinary size the distance between the armature and the poles is usually a matter of from one-eighth to one-quarter of an inch. The armature of the electromagnet, besides carrying a hammer with which the gong is struck, also carries on the side farthest from the poles a small flat spring, one end of which is attached firmly to the armature, the other end being sprung away from the armature and carrying, in the best bells, a small rivet of platinum wire. When the armature is in its normal position, the little spring at the back of the armature is held pressed against the point of a screw carried in a pillar called a contact pillar, the pillar being supported by the frame of the bell. One end of the wire wound upon the coils of the magnet is connected to the frame to which the armature is fixed by the spring first mentioned. The contact pillar, although carried by this frame, is insulated from it. The other end of the wire of the coil is connected to one terminal of the pole, while the contact pillar is connected to the other terminal. If, now, current enters the bell by the terminal connected to contact pillar, it passes from the pillar by the point of the screw to the platinum contact, and so to the armature, thence to the frame of the bell and so to the coils, after traversing which it leaves by the other terminal. If the bell is in adjustment and properly supplied with current, the armature will now be attracted towards the poles of the magnet against the holding-off effort of the spring which carries it. By its motion towards the poles of the magnet the armature does two things. It carries with it, in the first place, the hammer, which is thus given an impetus towards the gong, and it also carries with it the small contact spring on its back. This contact spring then ceases to make contact with the point of the screw in the contact pillar, and the circuit is thus interrupted, since the current will not traverse the small air gap between the point of the screw and the contact spring, although, for reasons which we will presently explain, a spark will be visible at this point. On the cessation of the current the magnet ceases to attract the armature, but the armature will not cease to move towards the magnet because it possesses inertia, and the armature and hammer having thus been set in movement towards the gong, will continue to move until their momentum has been destroyed by the joint action of the spring carrying the armature and of the impact of the hammer head upon the gong. As soon as the momentum has been destroyed, the spring carrying the armature brings it back in the reverse direction away from the poles until contact is again established between the screw on the contact pillar and the contact spring on the back of the armature. The armature is now in motion away from the poles, and again its momentum has to be destroyed before it can begin to move in the reverse direction under the attracting influence of the electromagnet. The momentum this time is destroyed by the action of the pressure exerted by the contact pillar through the spring on the back of the armature and the attractive force of the excited electromagnet. These forces then suffice to reverse the movement of the armature, and the whole cycle of operations is repeated, the action continuing so long as current is supplied to the bell. (*See further*, Section VI.)

ELECTROMAGNETIC APPLIANCES.

The uses to which the magnetic effect of an electric current is put are far too numerous and varied to permit of reference to all. Some, however, of the more important and more interesting of them may be described. Perhaps one of the most interesting is the substitution of an electromagnet for the ordinary hook at the end of a crane chain. In iron and steel foundries where large masses, often of odd shape, have to be lifted from one place to another, by far the greater proportion of time involved in the operation is occupied in attaching slings. If large castings have been left standing on the ground they may have to be prized up at one end and a chain sling slipped under, the operation being repeated at one or more other points, and care, as well as a considerable amount of skill and experience, is necessary for the proper adjustment of these slings. When once they have been attached the process of lifting and depositing on a trolley, and removing to the desired spot, is, of course, simple. In some foundries the bold step has been taken of hanging to the end of the chain a powerful electromagnet, the current to which is controlled from the crane driver's hut. The electromagnet entirely takes the place of both the hook on the end of the chain and of the slings that are ordinarily employed on the castings. If the casting be not in the best position for holding, the crane driver lowers the electromagnet on to it, switches on the current (the magnet holds on to the casting fairly well at almost any point), then turns the casting over until it is in the most favourable position for lifting. At the Sandycroft Iron Foundry, in Cheshire, for example, they have a device of this kind weighing about three hundredweight, and capable of lifting two tons. It is supplied with current at 110 volts, and takes about 5½ amperes, that is, just under one horse power. With it, three men are able to do in a quarter of an hour what formerly took the same number of men from two to four hours to do. In the same works another magnet is employed in a similar way almost exclusively for lifting finished lengths of shafting. The saving of time here is also very great, for the magnet picks up the polished shafts without the slightest risk of damage to them. It picks them up instantly and enables them to be lowered vertically, that is to say by vertical movement, while they themselves hang horizontally, into the boxes in which they are to be packed. A somewhat unexpected advantage accrues further, in that considerable saving is effected in the labour of packing and in the wood employed for boxes and packing. When the shafts were lowered into the boxes by means of slings, the boxes being wide enough for two shafts to lie side by side, space had to be left below the shafts and between them for the withdrawal of the slings, the shafts had to be packed up from the bottom of the box by distance pieces, and the margin of space between them had to be filled up by wooden wedges driven in tightly to prevent their moving during transit. With the present arrangement, the boxes are made to the exact lengths of the shafts, no tilting is needed is with slings to slip the slings off endwise, and the boxes are only just a trifle wider than is necessary for the two shafts to lie side by side. They are put straight into the bottom of the box, the current is switched off, no slings have to be removed, and a few very thin wedges or slips of wood are put in between them to prevent their damaging one another.

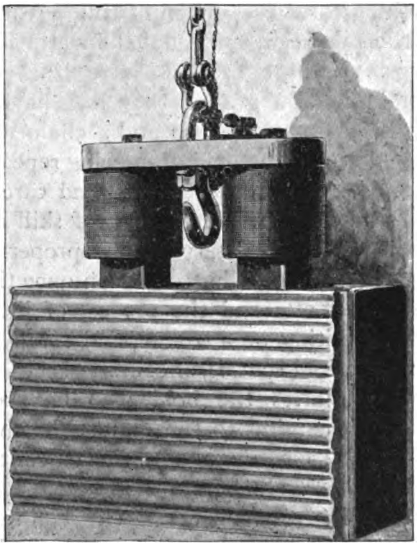


FIG. 150.—EXAMPLE OF CRANE MAGNET.

A further great saving of time is effected in certain mills, notably in those of the Illinois Steel Company in America, owing to the fact that, provided the stuff is not too hot, the magnets will lift hot forgings and castings, which would have to be let alone until they were considerably cooler if slings had to be used. In the mill referred to, an overhead traveller, driven electrically, is provided with a magnet capable of lifting five tons. When forgings or castings are at a dark red heat this magnet will easily lift three to four tons, and for these great loads the excitation of the magnet only requires about 4 amperes at 240 volts, or less than 1½ horse power. It is controlled by an ordinary switch in the driver's hut. At the same works electromagnets are used very largely for picking up rolled plates. They are in this way particularly serviceable when plates have been left lying on the ground flat, as they were rolled, and it is required to pick them up and set them on edge in the rack. Instead of having, as before, to raise one end of the plates and slip rollers under and get slings round, all that is now needed is merely to lower the electromagnet to the *edge* of the plate or plates, switch on the current, and begin to lift. The plates are then picked up on edge, and can be carried in that position, and stacked away in the rack. If the plates are very big or thin it is just as easy to employ two or three magnets suitably spaced to prevent sagging of the plates. An interesting "dodge" is in vogue at these works for the purpose of lifting one plate from a flat stack. When the current is turned on full the magnetic flux penetrates as a rule to a sufficient depth to enable several plates to be lifted at once, and if the crane is set to work to lift, that number will be raised. If, however, only one is required, the crane man rapidly switches the current off and on again. At each break, the magnetism, although falling off very greatly, does not die right away, owing to there being only a very small air gap where the magnet touches the top plate. The outside plates at each break fall away one after another, and thus by careful manipulation the man is able to drop them successively until he has the one remaining plate he desired hanging on to the magnet.

At Woolwich Arsenal the removal of large projectiles from the Store to the proving ground used to be a matter involving great labour and expenditure of time. For some years now, however, the slings have been replaced by an electromagnet designed by Major Holden, which picks the projectile up as easily as a boy's horse-shoe magnet will pick up a nib. The time and labour saved in the operation of stacking and unstacking projectiles for the large guns is extraordinary, a crane-man and one, or perhaps two, labourers being able now to serve them out on trolleys as fast as they may be required.

The obvious objection which would be at once raised to such uses of electromagnets is that they might at some instant fail. Such an objection is very reasonable, and it is indeed surprising that, seeing how easily an electric circuit may be interrupted, engineers have been found bold enough to adventure costly materials in such a way as has been described. So far, however, as the author has been able to discover, no accidents, at least none of any importance whatever, have occurred in connection with electromagnets used in this manner, and although the objection is certainly reasonable, it must be pointed out, on the other hand, that where anything like a large installation of electric power is available, the maintenance of the excitation of an electromagnet should not be a matter of less certainty than the proper adjustment of slings and hooks by the foreman labourer or ganger. At the same time it should be mentioned that in the last instance cited, viz., at Woolwich Arsenal, special precautions have been taken to prevent any accidental interruption of the supply to the magnet, the magnet having been provided with duplicate terminals and duplicate service wires running over pulleys to the source of supply. This particular magnet takes about as much energy as two ordinary incandescent electric lamps, namely, from 40 to 90 watts. It weighs about 45 lbs., and is capable of lifting two tons. This magnet is also provided with devices not

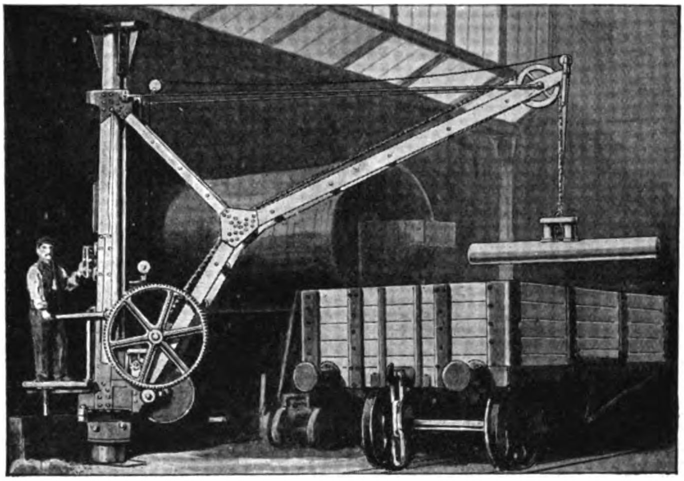


FIG. 151.—CRANE MAGNET.

employed, so far as the author is aware, with others, namely, with a water resistance which is switched in when the current is to be cut off, so that the latter can be cut off gradually, thus preventing a troublesome induced E.M.F. such as arises if the current is switched off suddenly. In view of the exceedingly small consumption of energy by the exciting coil, it is clear that this magnet would have a very high coefficient of self-induction which might well render this precaution necessary. (*See* Section VI.)

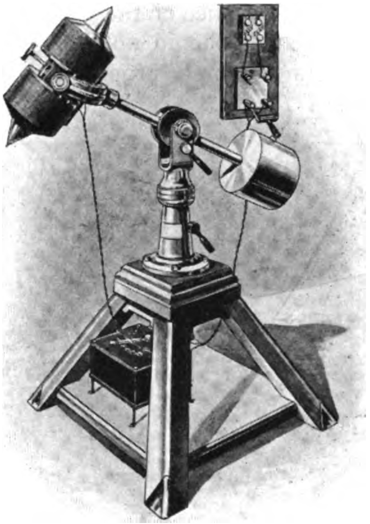


FIG. 152.—EXAMPLE OF OCULIST'S MAGNET USED FOR EXTRACTING PARTICLES OF IRON OR STEEL.

Passing now in the direction of smaller apparatus, an interesting electromagnet for use by oculists may be cited. The apparatus in question is a small but powerful electromagnet for extracting such fragments of steel or iron as are liable to be thrown into the eyes of grinders and other persons engaged in the hardware trades. One pole of the magnet is shaped to a somewhat fine point, which is, however, sufficiently rounded to prevent any risk of accidental damage to the eye. This point is brought into gentle contact with, or just outside, the wound where the iron or steel particle has entered, and current is then switched on. When this is done, the fragment of iron adheres to the point of the magnet, and can be drawn out. The extraction thus takes place completely and quite suddenly, leaving nothing for the surgeon then to do beyond the application of an ordinary dressing till the wound shall have healed. An apparatus of this description is designed for connecting to the lighting supply of a house; the magnet is supplied with variously shaped pole pieces, which can be attached at will, the suitability of the different shapes depending upon the position, etc., of the particle in the eye.

Electromagnets are, of course, the basis of all electric bell work, of indicators, telegraphs, relays, and telephones, and since they are fully described in this connection in the sections dealing with telegraphy and telephony, reference is now made to those sections for a description of such apparatus.

An extremely interesting application of magnetism is to be found in the railway signal system due to Mr. W. S. Boult, A.M.I.C.E. By this ingenious system Mr. Boult has succeeded in delivering the signals to the cab of the engine in such a way as, ordinarily speaking, to preclude any possibility of failure or mistake. When it is realised that at present a driver has to look out for the position of a semaphore arm by day, picking out the right one from a number of others, has to do the same thing with a coloured light at night, and in foggy weather has to regulate his actions in accordance with the explosions of a number of detonators, it will be recognised that a system which gives only one kind of signal by day or by night, in fair weather and foul, and that signal, moreover, on the cab of the engine under the very nose of the driver, has very marked advantages over those ordinarily in use. The means by which Mr. Boult attains his end is magnetism. Broadly outlined, the system consists of transmitting to a piece of iron carried by the engine, magnetic polarity from magnets that are placed in the roadway, the polarity depending upon the signal to be given. The magnetic flux enters this piece of soft iron, and is conducted by it to a polarised relay which effects the signals. The relay, the battery, and all the working parts on the engine are provided in duplicate, and fault indicators are inserted in the circuits, so that the risk of any breakdown is brought to a veritable minimum, since it is most unlikely that both the duplicated parts should break down at once; and if one of the two does fail, the fault indicator at once draws the engine-driver's attention to the fact. The magnetic field which operates the relay is produced either by permanent or electromagnets placed in the track. In order to reverse the signals of the permanent magnets they are mounted on a shaft of brass, so that they can be turned end for end by a half-revolution of the shaft. The reversal of electromagnets, if used, is, of course, simply effected by reversing the direction of current through the winding. The iron armature carried by the engine simply collects magnetism from the poles of the track magnets. The latter are placed either between the running rails or, as preferred, to one side of them. In some trial runs on the Great Central Railway, the arrangement adopted was that of seven permanent magnets mounted on a brass rocking shaft, each magnet being provided with a soft iron extension to one pole in the shape of a quadrant. These quadrants were united at the top to a bar which held them rigidly together, and the whole arrangement was boxed in so as to be protected from weather, dirt, and unlawful interference; the collector on the engines was arranged to pass over the tops

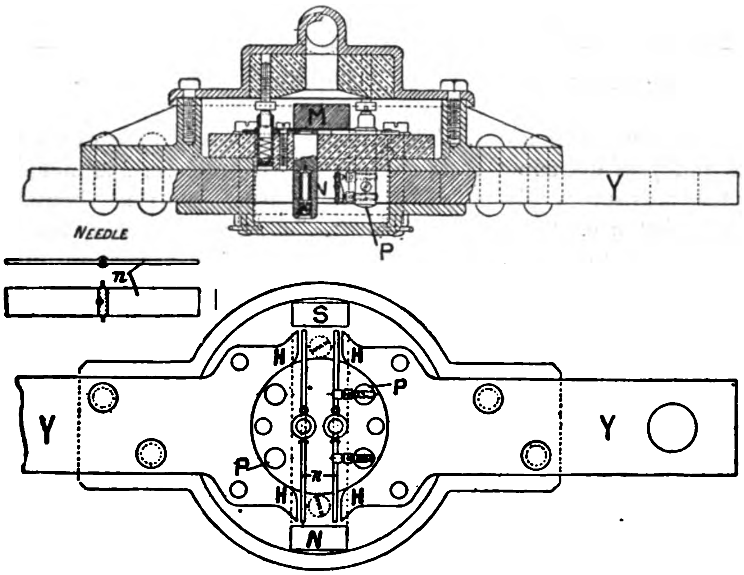


FIG. 153.—POLARISED RELAY OF BOULT'S SIGNALLING SYSTEM. M, POLARISING MAGNET; N, S, POLES OF DITTO; Y, IRON YOKES CARRYING FLUX TO HORNS H, H, FROM MAGNETIC COLLECTOR NOT SHOWN. P, CONTACT POSTS; *n*, NEEDLE.

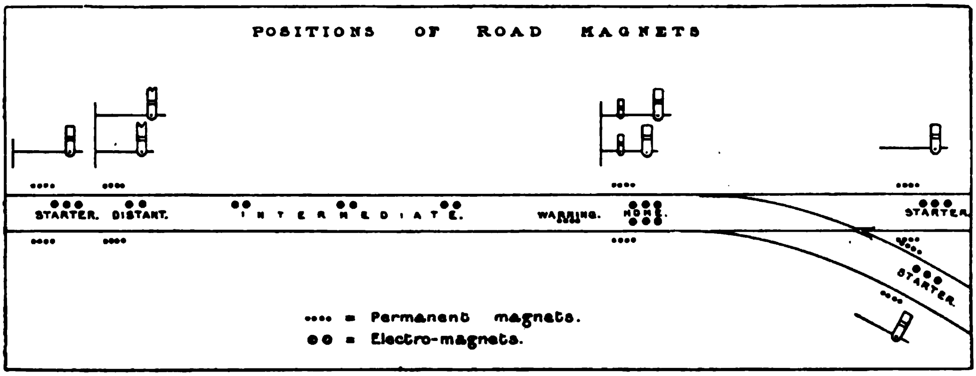


FIG. 154.—DIAGRAM OF BOULT'S SIGNALLING MAGNETS.

of the soft iron quadrant extensions. The collector need not pass extremely close to them, as the field was sufficiently powerful to act across a fair distance. With the magnets in the position to give the "line clear," all that had to be done to give the veto or "danger" signal was to rock the shaft through half a revolution. A weight was provided at one end of the rocking shaft to pull the magnets over, ordinarily, to the danger position, and they were pulled into and held at the "line clear" position by the signal wire; consequently, if the wire broke, there was no fear of a "line clear" signal being given; and not only so, but the "danger" signal was bound to be given. Mr. Boult's apparatus has been tried with absolute success at 70 miles per hour on the Great Northern Railway.

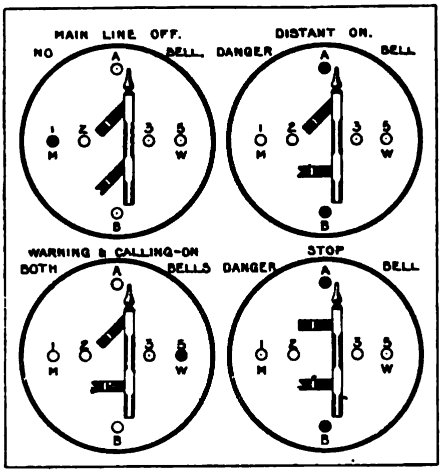


FIG. 155.—INDICATOR CARRIED BY ENGINE IN BOULT'S SYSTEM OF SIGNALLING.

MAGNETIC SEPARATORS.

A very interesting but little heard of application of magnetism to commercial purposes is to be found in the numerous magnetic separators that have from time to time been devised and made. As their name implies, these machines are designed to separate mixed materials into two or more classes by magnetic means. At first sight it would appear that such machines have a very limited application, and, of course, this was so at first, but, like so many other applications of scientific principles to commercial purposes, the originally limited use of magnetic separators has of late years become very much extended, and in directions which are at first sight surprising.

When first introduced, magnetic separators were almost exclusively used for dealing with sweepings from workshop floors when those sweepings contained fragments of both iron and brass in mixture. The brass turnings and filings being of considerably more value than iron ones, magnets were employed to separate the iron and steel filings from the brass, copper, or zinc, or other non-magnetic material. Very simple apparatus of this description, consisting of permanent magnets beneath which a leather band travelled carrying with it the mixed filings, were quite successful, and for a long time underwent little development.

The next application appears to have been in the preparation of iron ores for smelting, in which magnetic separators were employed to deal with the crushed mineral and to extract from it the iron-containing portions, allowing the merely earthy non-magnetic mineral to pass through the machine and be thrown away. An example of apparatus dealing with material in this manner is illustrated in Fig. 156. Their use, however, does not terminate here. Iron is by no means the only magnetic material, although it is, of course, by far the most common. Nickel and cobalt are quite appreciably magnetic, and are of considerably greater value than iron, so that their recovery in small quantities is a matter of considerable importance. Oxygen, too, in the liquid condition, is quite strongly magnetic, and it has even been suggested that air should be liquefied, and the oxygen separated from the nitrogen in a magnetic separator, when the nitrogen could be allowed to escape, and the oxygen retained for commercial purposes. After the separation has been effected the heat absorbed by the liquids in returning to vapour could be taken from further supplies of air, thus facilitating its liquefaction. This suggestion does not sound very feasible, and does not appear to have been put to any practical test.

A further application of great ingenuity is the separation of gold and silver, which are neither magnetic nor strongly diamagnetic, from sand and gangue. The mixed material is allowed to fall in a thin sheet past a very long magnet pole whose length lies horizontal. As the metallic portions move into the magnetic field eddy currents are generated in them, and they are repelled from the magnet pole. The non-magnetic material, sand and crushed rock, is not thus acted on, and falls with its course unchanged. Below the magnet are two receiving chambers, into one of which, immediately below the magnet, the sand and rock fall, while the metallic particles are retained in the other placed near by.

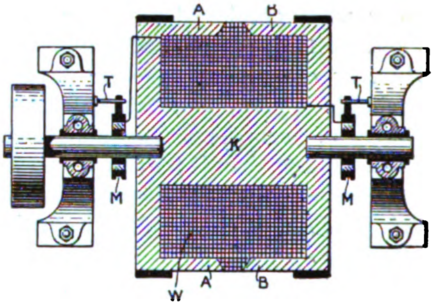
Another interesting device, due to Mr. Edison, for the recovery of gold from gangue, consists in first of all submitting the whole mixture to an electro-plating operation, in which the metallic particles only, of course, take part, and in which the deposited material is iron. The mixture with the gold, silver, copper, etc., now electro-plated with iron, is then submitted to the action of a magnetic separator, which retains the coated material, allowing the sand, etc., to escape as before. The iron coating is exceedingly slight and porous, and the metal is allowed to pass into amalgamating troughs of quicksilver, from which the precious metals are recovered in the usual way.

Another and most valuable application is the extraction of iron from clay intended for use in pottery. It is a matter of the utmost importance to the manufacturer of white porcelain that his materials shall be as free as possible, in fact, absolutely free, from all particles of iron or iron compounds, since these when fired would occasion coloured blemishes in the finished ware. The materials are ground wet to an impalpable powder and form a kind of sludge. Then magnetic separation is brought into play, and all the ferric materials are thoroughly extracted.

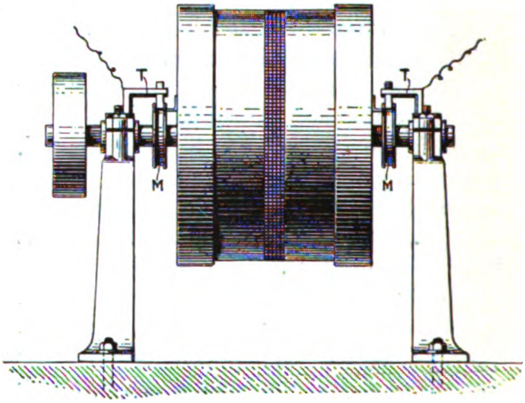
It is very surprising to find in how many industries there is danger of particles of iron and steel becoming mixed with materials from which they should be entirely absent, and in how many such cases magnetic separation has actually been employed. For example, the wheat that has been harvested by machinery is liable to have small particles of iron and steel in it which would damage the rollers or stones of the grinding machinery ; the material incorporated with paper pulp is reduced to that condition by steel grinding machines ; cotton seed, and, indeed, an almost endless variety of materials, are ground in steel or iron mills, and in all these cases, and in those enumerated, magnetic separators are employed to cleanse the material from the foreign particles of iron or steel.

A machine for separating metallic and non-metallic materials, allied to, but quite distinct from, magnetic separators, is worthy of mention, and may be referred to here. In it the mixed material is made to fall through a region occupied by a very strong electrostatic instead of magnetic field. The metallic particles become deflected by the action of the electrostatic field and are caught in a separate receptacle, while the sand or other non-metallic material continues its ordinary course and escapes. This device is, of course, applicable to any metals whether magnetic or not, and is therefore of service in the separation of gold, or copper, or zinc from the metalliferous ore. Of this machine, however, the author has been unable to trace any actual use.

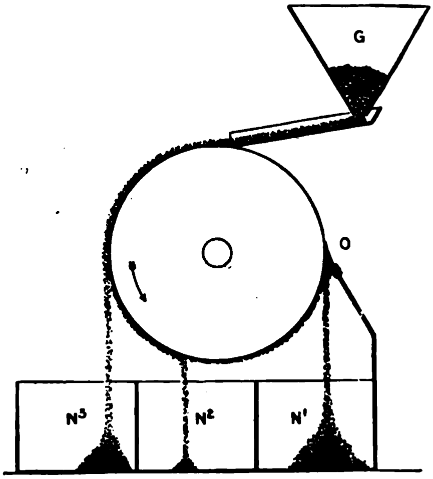
Electromagnetic devices are very conveniently employed in clutches for machinery, in brakes for tramcars, in chucks for holding the work for lathes and on planing machine tables ; examples of a lighter sort are to be found in ingenious arc lamp mechanisms, in measuring instruments, signalling apparatus generally, and telegraph and telephone instruments. Space will not permit of detailed notice of many of these, but reference to typical examples will be found in the sections dealing with the respective branches of the subject.



SECTION.



ELEVATION.



GENERAL ARRANGEMENT.

FIG. 156.—MAGNETIC SEPARATOR.

N 1, HIGHLY MAGNETIC MATERIAL ; N 2, SLIGHTLY MAGNETIC ; N 3, NON-MAGNETIC. T, TERMINALS ; W, WINDING ; A, B, POLAR SURFACES ; K, CORE ; O, BRUSH ; G, HOPPER.

CHAPTER IV.—MAGNETO-ELECTRIC INDUCTION.

RULES FOR DIRECTION—RATE OF CHANGE *v.* RATE OF CUTTING—NUMERICAL EXAMPLES—EDDY CURRENTS.

MAGNETO-ELECTRIC induction is the name given to one of the most interesting and probably the most useful of all the phenomena of magnetism and electricity. It may be said to be the simple cônverse of electro-magnetism, that, as an electric current may be made to produce magnetism, so magnetism may be employed to produce an electric current. This statement, although appearing rather vague, really conveys the essential principle involved.

With his marvellous insight into natural phenomena, Faraday, after having investigated almost all the magnetic effects of currents, foresaw, or at least anticipated, that magnetism might be made to induce currents. Experiments which cannot be detailed here, but which fill the reader with wonder and admiration almost beyond words, are recorded in his notes at the Royal Institution, showing how, step by step, he wrung from nature the secret which he suspected. These experiments prove that there must be relative motion between a conductor and a magnetic field, in order that a current may be induced in the former. Of course, the current is the result of an electromotive force, and it is therefore better to say that an electromotive force is induced; this is clearly so, since we may have an electromotive force but no current if the resistance is infinite. Further we find that if everything else is kept unchanged, the current induced is inversely proportional to the resistance in the circuit, and that an electrostatic voltmeter which allows *no current* to pass through it may be used to indicate the induced E.M.F. when no appreciable current is generated. The fundamental phenomena are best grasped by a study of the following experiments.

In Fig. 157 the magnet M is shown as having its N pole thrust into a coil of wire, C, the final position of the magnet being shown in dotted lines. Let us suppose this operation to generate an E.M.F. in the conductors forming the coil such that a deflection to the right is produced

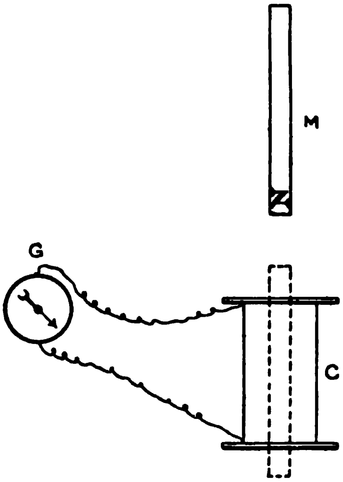


FIG. 157.—DIAGRAM ILLUSTRATING INDUCTION OF A CURRENT IN A COIL.

on the galvanometer G. This deflection only occurs during the motion of the magnet, being, as a rule, of an observable magnitude just before the end of the magnet reaches the coil, increasing as the end enters the coil, and keeping at a fairly steady value till the magnet is stopped, when the current instantly ceases. If the motion of the magnet be continued until it reach the dotted position shown, the current will die down to practically nothing before the magnet has stopped. If, when the magnet is in the dotted position it be taken out again, a deflection to the left will be produced, no matter whether the magnet be dropped right through or pulled up. If the magnet be moved as indicated in any of the ways indicated in Fig. 158, no effect will be produced, provided everything is symmetrical, and if the magnet be dropped from some little distance clean through the coil, practically no effect will be produced. If, however, any of the operations indicated in Fig. 159 be performed, an E.M.F. will be generated and a deflection produced on the galvanometer. The magnet is supposed to be moved from a full line to an adjacent dotted line position in the figures.

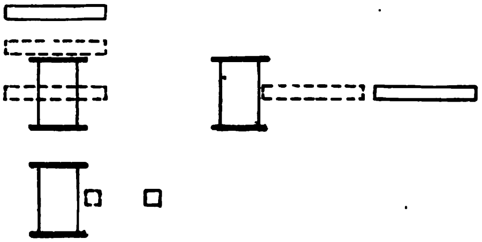


FIG. 158.—DIAGRAM ILLUSTRATING MOVEMENTS WHICH DO NOT GENERATE AN E.M.F. IN THE COIL.

These simple experiments show conclusively that the mere presence of a magnet in or near a coiled or straight conductor is not sufficient to give rise to an electric current; there is at least one other essential, and that is relative motion between, apparently, the magnet and the conductor; and even that does not always suffice to produce a current. For the present we will assume that we are right in concluding the motion to be necessary as between the magnet and the conductor. This essential is, of course, present in the experiment in which the magnet is dropped from some little distance clean through a coil, and yet, although in that case we had the magnet, the coil, and the relative motion, there was no observable electromotive force or current.

In order to understand the reason for these phenomena and for the apparent contradiction in the last case, let us remember what was referred to in Chapter II. of this section. We there saw that the whole of the space surrounding a magnet is permeated with forces constituting a magnetic field which we regard as composed of these lines. Now consider what happens between the conductors forming the coil and the lines of force forming the field. Consider what will occur if the coil

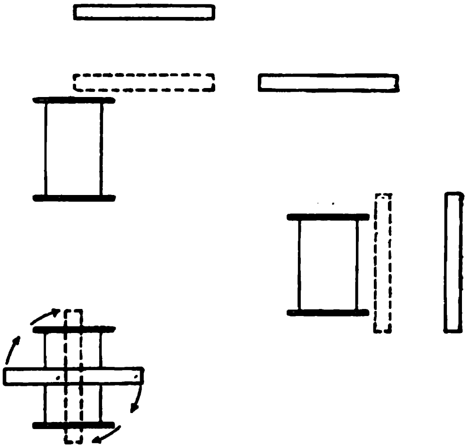


FIG. 159.—DIAGRAM ILLUSTRATING MOVEMENTS WHICH DO GENERATE AN E.M.F. IN THE COIL.

in Fig. 160 successively occupies the various positions shown. It is quite clear that just as the magnet begins to enter the coil, the field, or rather the lines of force of which it is composed, have to pass in some way *through the conductors* of the coil, that is to say, there is an apparent *cutting* either of the conductors by the lines or of the lines by the conductors. This apparent cutting must not be supposed to have any actual severing effect either on the conductors or, so far as we know, on the lines. We have, however, to imagine some process to account for the passage of the lines from a position quite outside the coil to a position such as that marked 2 in Fig. 160. The most obvious thing to imagine is that the lines of force are cut as they pass the conductors, and instantly join up again, and this would lead to the conclusion that a cutting of lines of force by the coil is the condition essential to the production of E.M.F., and hence of a current. Now let us examine this conclusion as it affects the direction of the current.* The direction of the current has been indicated as being, in one sense or the other, by the deflection of the galvanometer, which, in some cases, was to the right and in others to the left, and if we test what direction of current is needed to produce a deflection to the right by connecting a cell to the coil and galvanometer, we shall arrive at the following results: When the north pole of the magnet is caused to enter the right-hand end of the coil which is now shown enlarged in Fig. 161 for the sake of clearness, we find that the direction of the current* is that indicated by the arrows on the conductors, the movement of the coil being also indicated by an arrow. This one test is, of course, a key to all the others, for our former experiments show that if we pull the north pole away from the coil or the coil from the pole, we reverse the current, or if we make the south pole approach the coil we also get a current in the reverse direction of that indicated in Fig. 161. If we now refer to our rules for direction of flux produced by a current, we see that the relative movement of the coil and magnet in each case produces in the coil a current of such direction as would generate a flux in the coil opposite in its direction to the flux which is being introduced by the motion. For example, in Fig. 161, where we have a north pole entering the coil, and may be therefore said to be introducing a field which shall traverse the inside of the coil from right to left, we find that the current

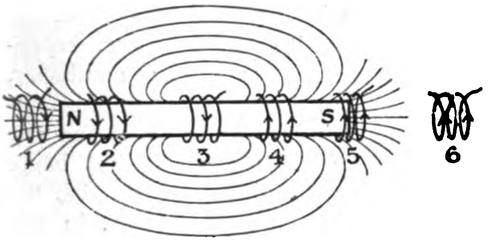


FIG. 160.—COIL MOVED TO CUT THE FIELD OF A PERMANENT MAGNET.

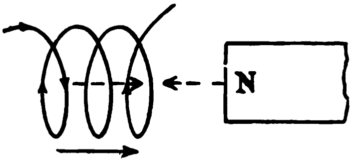


FIG. 161.—DIAGRAM SHOWING DIRECTION OF INDUCED E.M.F. IN A MOVING COIL. THE FULL LINE ARROW INDICATES MOVEMENT OF COIL. THE DOTTED ARROWS INDICATE FLUX.

---

* In the figure the ends of the coil are shown for clearness disconnected from any circuit. This would, of course prevent any current from flowing at all, but would still permit of an E.M.F. being generated, which would drive a current if the circuit were complete.

* *See* footnote in previous column.

generated by the introduction of this field is in such a direction that it, of itself, would produce in the coil a flux from left to right. If, on the other hand, we pull the magnet out of the coil and may thus be said to be *robbing* the coil of a field which flowed from right to left, we find that the induced current is reversed, and is in such a direction as to *produce* a field from right to left; and that in every case, no matter which pole of the magnet is nearest the coil and no matter what the relative motion, the current generated by the change always tends to *oppose the change.* This conclusion will also hold good whether the coil has already got a field of its own or not, and hence no matter what the state of the coil may be to begin with, it is found experimentally that, whatever the magnetic change set up by the motion of a magnetic field relatively to the conductors of the coil, the effect of that change is to set up an E.M.F. tending (by a current) to oppose that change. This conclusion is of the utmost importance in experimental work, and the statement of it is known as Lenz's law.

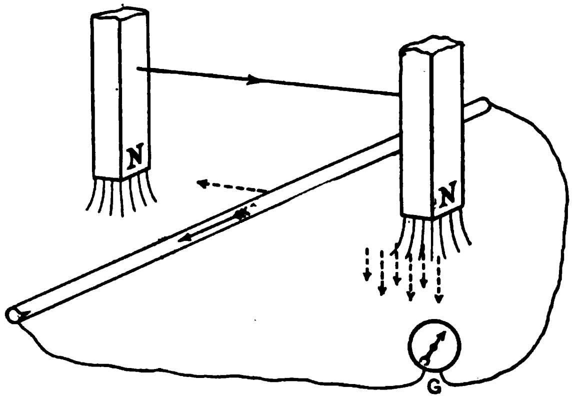


FIG. 162.—DIAGRAM SHOWING DIRECTION OF E.M.F. IN CONDUCTOR BY MOVING MAGNET. THE MAGNET IS MOVED AS INDICATED BY THE FULL LINE AND ARROW HEAD, OR THE CONDUCTOR AS INDICATED BY THE DOTTED ARROW.

The cases illustrated in Fig. 158, and which appear paradoxical, are very simply explained. In each case an E.M.F. is set up in each conductor cut by any lines, but the movement is such that half the flux passes one way and half the opposite way across the conductors. Hence, there are two sets of opposing E.M.F.'s which are equal to each other. One set neutralises the other and no current is produced.

The experiments we have described involve conductors that have been wound into coils, but it is quite easy to show, experimentally, that any conductor, when subjected to changing magnetic influences, becomes the seat of an E.M.F., and it has hence become common to describe the induction of an E.M.F. in this way as being due to the "cutting" of lines of force. In the case of a single straight conductor this is quite simple and cannot well lead to confusion or error. If a magnetic pole be moved past a straight conductor (Fig. 162), lines of force must obviously move across the conductor, and as before, the conductor "cuts" the lines. The movement of the magnetic pole in one direction will tend to produce a current whose field is in the opposite direction, and in no case is there any current induced unless the movement of the magnet is in such a direction that the field moves across the conductor. A very little consideration of the experiments detailed in Fig. 159 will show that the same rule holds good for the coil. In no case was an E.M.F. produced in that coil unless the lines of force in their motion were actually cut by the conductors. A glance at Fig. 162 shows us that we really have three prime directions to deal with. Firstly, the direction in which the conductor lies, and along which, therefore, the current has to flow, either one way or the other; secondly, the direction of the magnetic field itself, which is at right angles to the direction of the conductor; and, thirdly, the direction of the motion, which has to be at right angles to the other two. We thus have three directions in space, all at right angles to one another like the directions of the three lines in the corner of a room where the two walls and floor meet. These three directions may be represented fairly well by the thumb and the first and second fingers on one's hand; and since Lenz's law is not always easily applied to a straight conductor, Dr. Fleming has given an extremely simple and useful rule for determining the direction of the induced E.M.F. by reference to these fingers. Since the rule has most commonly to be applied to conductors which we move past magnets, and not to the movements of magnets past conductors (which we have been considering) it must be carefully borne in mind that Professor Fleming's rule applies to *conductors moving* past stationary magnets. Professor Fleming says that if the thumb and two fingers of the *right* hand be all set at right angles to one another, as in Fig. 163, then if the forefinger represents lines of force and the thumb the direction of motion of the conductor, then the second finger will point along the direction in which the E.M.F. acts, and in which, therefore, the current, if any, will flow.*

We thus have now two simple rules for the direction of the induced E.M.F., Lenz's law being applicable at once and easily to a coiled conductor, and Fleming's rule to a straight conductor. It will be found most generally useful to apply these two rules in this manner, but it will be as well at once to point out that the two rules are perfectly consonant, as may be seen from the following consideration: In Fig. 162 we have shown a straight conductor, the two ends of which are connected to a galvanometer, for the purpose of detecting the presence of the E.M.F. If, now, the magnet M be moved in the direction shown by the arrow, the conductor will cut lines of force, and we can apply Fleming's rule. Bearing in mind that Fleming speaks of movement of conductor past a fixed magnet, we see that the equivalent motion of the conductor, supposing the magnet to have been held still, is that indicated by the dotted arrow, and that the E.M.F. by Fleming's rule will therefore act in the direction shown by the arrow drawn on the conductor. To apply Lenz's law, we may consider the conductor, the galvanometer, and the wires connecting them as forming *a coil of one turn*. The movement of the magnet has therefore introduced into this single-turn coil a field

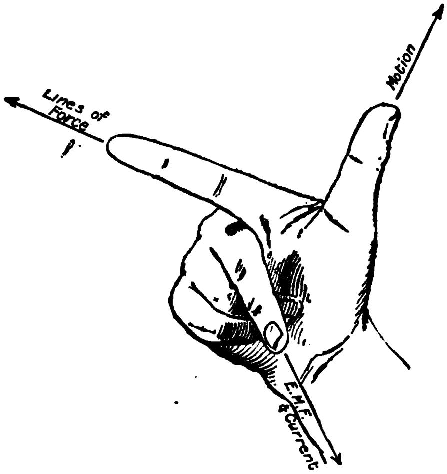


FIG. 163.—DIAGRAM ILLUSTRATING FLEMING'S RULE.

---

* A convenient mnemonic for this rule may be made thus:—

FORe-finger represents lines of FORce.
sECond finger „ direction of E.M.F. and C-urrent.
ThuMB „ direction of M-otion of B-ar.
Right hand is *right*.

threading it, as indicated by the little group of dotted arrows and, according to Lenz's law, the current generated would be such as to oppose this change. We see at once that the current we arrive at by Fleming's rule will oppose the change, and hence that either of the two rules gives the same result, although they are not equally convenient for all cases.

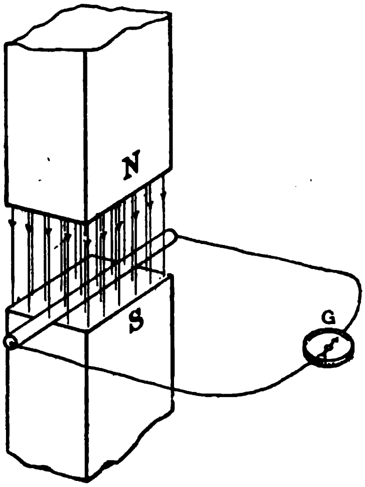


FIG. 164.—DIAGRAM SHOWING HOW THE RULE REGARDING "CHANGE OF LINES ENCLOSED" MAY BE APPLIED TO A STRAIGHT CONDUCTOR.

RATE OF CHANGE *v.* RATE OF CUTTING.

Next in importance to a determination of a rule for the *direction* of the generated E.M.F. is, of course, the need of determining the conditions which affect the *magnitude* of the induced E.M.F. These conditions might be illustrated by the following experiments: Let the ends of a straight conductor be connected to a galvonometer as was shown in Fig. 162, and let the observer be provided with a number of small bar magnets of precisely equal strength. The galvanometer should be a low resistance one of the aperiodic type (*see* Section V). Now let the observer move the pole of one of the magnets past the conductor at a convenient rate. He will produce a current and a deflection on the galvanometer. Now let him move the same magnet as nearly as he can at double the previous rate. He will find that the deflection on the galvonometer is roughly twice as great as it was before, although, of course, it will only last for half the time. Now let him take two magnets, holding them in such a way that all cross the conductor at the same instant with their similar poles together, and then three, four, and so on, and he will find in all cases that the magnitude of the current produced will be increased correspondingly, and will be proportional to the rate at which the lines are cut by the conductor. If he move four magnets past the conductor he will get twice the current that he would if he moved two past it at the same rate, or the same current that he would obtain by moving eight past the conductor at half the rate used with the four. We have spoken of currents, but since the resistance of the circuit remains constant the currents will, of course, be proportional to the E.M.F. producing them, and since each is due to an E.M.F. produced by the cutting of the lines, it is of the E.M.F. we should speak rather than of the current, for the current will depend upon the resistance of the circuit, whereas the E.M.F. will not. We are thus led to the statement that the E.M.F. generated is proportional to the rate of cutting of lines of force by the conductor, and it has been common in textbooks to speak only of this. Now, although this statement is perfectly accurate, it becomes difficult in some cases to apply it properly to the whole of the circuit, and the author has during the past twelve years met with numbers of students who have quite failed to apply this rule carefully to every part of a complicated circuit, and have thus been led to design what they considered to be improved forms of dynamos, which on careful examination proved to be incapable of generating any E.M.F. whatever. The author may perhaps mention one case which came to his knowledge in which the student could not be satisfied by argument that the machine would generate no E.M.F., and went to the heavy expense of having a small machine made, which only too well illustrated the error of his ideas. In view of this, students and beginners will find it particularly useful to check any conclusions they arrive at from considering the *rate of cutting* of lines, by a consideration of *rate of change* of lines enclosed. The two rules for direction we have given above involve these two ideas respectively, Fleming's rule involving the idea of cutting, Lenz's law involving the idea of a change in the number of lines threading the coil; and it was shown that even in the case of a straight conductor the circuit may always be completed, even if it be only by a galvanometer, so that Lenz's law may without great difficulty be applied even to a straight conductor. The condition, then, which determines the magnitude of an E.M.F. induced in a circuit is the rate of change in the number of lines threading that circuit, and the safest test to apply to a circuit to see whether an E.M.F. will be generated in it is to see whether there is any change in the number of lines threading it.

Here again it will be well to show that whichever way the condition is stated it will give us the same result. In Fig. 164 a conductor is shown connected to a galvanometer and placed in a magnetic field of uniform strength indicated by the arrows. Suppose the field strength to be one line of force per square centimetre, and let us suppose the conductor to be ten centimetres long and to be moved across the field at the rate of 100 centimetres per second; we must suppose the two end wires connecting the conductor to the galvanometer to be used to pull the conductor across the field, and in order that they may produce no cutting let us suppose them to be kept truly at right angles to the conductor. If now we apply Fleming's rule we shall find that the conductor is cutting 1,000 lines per second, and that the E.M.F. generated in the circuit may therefore be represented numerically by the number 1,000. It, on the other hand, we apply Lenz's law we find that when one second has elapsed the movement of the conductor has *excluded 1,000 lines from the embrace of the circuit* and that hence we have in one second a change of 1,000 lines threading the circuit, or in other words a rate of change of 1,000 per second giving as before a numerical value of 1,000 to the E.M.F. produced.

EDDY CURRENTS.

There is one case of magneto-electric induction of special interest. If a magnetic pole be moved over the surface of a sheet of metal, say copper, the lines of force from the magnet will take some path, such as that indicated in Fig. 165, through the sheet, and the movement of the magnet will therefore involve relative motion between the copper, which is a conductor, and the magnetic field. This will result in the generation of E.M.F's., and it only remains to be seen what the directions of these are. This is most easily arrived at by supposing the copper sheet just beneath the magnet to be made up of a number of strips of metal whose length lies at right angles to the direction of motion of the magnet; three such strips are indicated in the picture. From what has gone before it will at once be seen that an E.M.F. will be set up in the strips immediately under the pole and that the general direction of the induced E.M.F. will be that of the arrows. If we next consider the region of the copper surface in front of the strips and into which the field is being introduced by the motion of the magnet, we shall find by Lenz's law that a field of the opposite direction would be produced by currents flowing in circular paths as indicated by the arrows. On the other hand, the region behind the strips is losing a magnetic flux by the onward motion of the magnet and should have currents opposing the change, (that is maintaining the field) in the direction indicated there by arrows. These various currents, which we have considered in three groups, combine in reality to flow in circuits indicated in Fig. 166, the paths which they take being, of course, free to them, since the copper is one homogeneous whole and not made up of strips as we had just imagined.

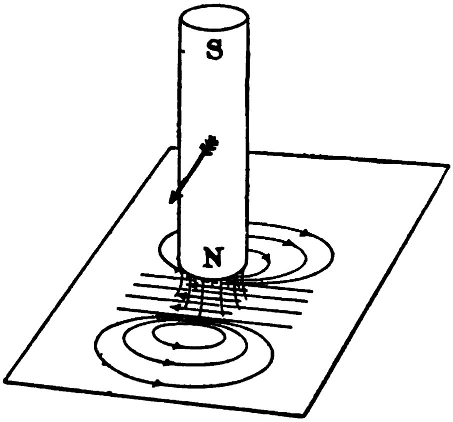


FIG. 165.—EDDY CURRENTS INDUCED IN COPPER SHEET BY MAGNET MOVING ABOVE IT.

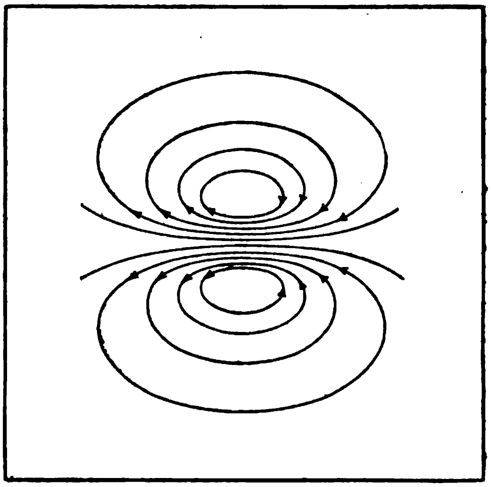


FIG. 166.—PATHS OF EDDY CURRENTS IN COPPER SHEET OF FIG. 165.

SECTION V.

INSTRUMENTS AND TESTING.

CHAPTER I.—UNITS.

UNITS—LENGTH, MASS, AND TIME—UNIT MAGNET POLE—UNIT CURRENT STRENGTH—UNIT E.M.F.—UNIT RESISTANCE—AMPERE, VOLT, AND OHM—COULOMB, WATT, JOULE, FARAD, MAXWELL, GAUSS, AND HENRY—CONCRETE STANDARDS—HEATING EFFECT.

THE whole of the processes of testing which are carried out in connection with electrical science may be classified broadly under two heads—those which are of a laboratory nature, and those which are capable of being carried out in the test room of a manufacturing works. The principal differences which separate the two classes of testing are that the quantities to be measured under the first heading are usually very much smaller, and the instruments employed much more delicate, than those dealt with and employed under the second or commercial heading, and that the accuracy desired in the second class is rarely so high as that sought in the laboratory. It is the constant endeavour of engineers to provide instruments and processes which will enable them in the test room of a factory to rapidly and accurately apply tests of quality to the materials they employ, and tests of efficiency and accuracy to the machinery and apparatus that they manufacture. The ground work of success in all these endeavours must invariably lie in the laboratory, and in taking up the question of testing, it will be well to commence with the consideration of the quantities to be measured and the instruments to be employed in the electrical laboratory. Since all observations or measurements which are to have any practical value must be made in terms of some clearly defined unit, it is of the utmost importance to have both an accurate definition of the units by which the various quantities concerned are to be measured and accurate standards embodying these units. The former has already been settled for us, thanks to the combined labours of various committees, international in their character, which have sat in Paris and elsewhere: the latter have to be reproduced from time to time, and here further we have the assistance of the Board of Trade suggestions and advice to guide us in the selection and design of materials and apparatus. The whole system of measurement in electrical and magnetic science is built up from the three fundamental units from which all physical measurements must take their origin, namely, those of length, mass, and time. The units employed for the building up are those adopted by the French Congress, and known respectively as the centimetre, the gram, and the second. These three units have been accurately defined, and means for measuring them have been widely afforded.

LENGTH, MASS, AND TIME.

The centimetre was originally defined as the hundredth part of a metre, which was supposed to be the ten millionth part of a quarter of the earth's circumference. The metre as first determined, was not, as subsequent measurements proved, precisely that fraction of the earth's circumference, owing to errors made in measuring the earth. The error having been measured in turn, however, the metre may still be regarded as a fairly rational standard, and standard metres, decimetres, and centimetres are preserved in the archives in Paris. Great importance naturally attaches to the accurate determination of the unit of length, because from it, in point of fact, all others spring. Given an accurate standard of length and reasonably easy means of verifying that standard, we have at once at our disposal the means of establishing every other conceivable unit. Take, for example, the unit of mass. Having obtained the unit of length, we can at once from that construct a unit of volume, and have then only to fill it with some substance selected as standard, and which may be selected quite arbitrarily. The unit of mass would then be the quantity of matter contained in the unit volume of that standard substance. Even the remaining fundamental unit, that of time, may be arrived at by reference to length. We need only specify the exact length of a pendulum, and state where that pendulum is to be used, and we at once have, in the actual time of swing of this pendulum, a standard unit for the measurement of time. In the metric system the unit of mass is called the gram, and is defined as the mass contained in a cubic centimetre of water at its temperature of maximum density.

It is interesting to notice the consideration which led to the selection of water as the standard substance for the definition of unit of mass. In arbitrarily selecting a substance for this purpose it is obviously desirable to select one which can be readily obtained in a state of purity, and which further can be obtained at a low price. Water, of course, fulfils both these conditions admirably. For all purposes of purely physical measurement water may readily be obtained in a state of sufficient purity by distillation, and it is, of course, obtainable without difficulty. Further, in the selection of the temperature at which the cubic centimetre shall hold unit mass, we have an extremely simple means of defining this temperature without reference to any thermometric scale (which of itself is necessarily arbitrary). Water, by reason of its peculiar behaviour at about a temperature of 4° Centigrade, provides us with a reference to temperature which is entirely independent of any arbitrary scale. On being heated from the temperature of melting ice it at first contracts, and hence increases in density, but on arriving at a temperature of almost exactly 4° Centigrade it commences to expand, and from that point up, until its conversion into steam, it expands under further heating. By this behaviour it passes through a condition of maximum density, and so affords a most convenient reference to density which is inherent in itself, and the Paris Congress could hardly have done other than select this material, which embodies in itself the three properties most desirable in a standard substance.

The metric unit of time is, in point of fact, a very old unit of time, for it was decided that, as the second had been so accurately determined and was so well known a unit, it would be better to define the second in terms of metric measurement rather than to introduce a new unit of time which might have had a rather simpler connection with the metric system. The second of time is hence now defined as the natural time of oscillation *at Paris* of a pendulum whose true length is

99·39 cm. At first sight it would appear that these fundamental physical units have little to do with the measurement of magnetic or electric quantities. Such, however, is not the case, for the whole of our extended but simple system of electromagnetic measurements is based entirely on these three fundamental quantities. If we begin with magnetism, we find, of course, as in every other physical science, that we have to measure quantities entirely by one of the effects they are capable of producing. The most obvious effect of magnetism is the attraction or repulsion of oppositely or similarly magnetised bodies respectively. Hence we should seek to base some unit for its measurement on the existence of this force. But if our unit is to be connected with the C.G.S. system (this is the commonly used abbreviation for the metric system, the letters employed being the initials of the words centimetre, gram, and second), we must frame in that system a unit of force. This is readily done. If a force act on a mass it will accelerate the mass. The acceleration will be positive or negative, according as the force increases or decreases the velocity, that is according as it assists or opposes the motion. Obviously the unit of force, then, should be that force which, acting on unit mass for unit time, should in that time change its velocity by unit amount. The attempt to define this at once brings us to the necessity for defining a unit for velocity. This, again, can readily be done by reference to the three fundamental units, for clearly unit velocity should be that at which unit space is passed over in unit time. Hence the unit of velocity should be one centimetre per second. Going on, then, to the definition of a unit force, it should be a force such that if it act upon one gram for one second it will change the velocity of that gram in that second by one centimetre per second. The definition as here expressed is not in all cases strictly accurate, but has been put thus for the sake of simplicity. This definition breaks down if the force acts for less than a second,* and if stated properly should run as follows: The unit of force is that force which will give unit mass unit acceleration; or, in terms of the units, a unit force will accelerate one gram one centimetre per second per second. This force is called the dyne. We can now proceed to the magnetic definitions.

UNIT MAGNETIC POLE.

We shall first of all want a standard for the pole strength of a magnet, and, since the force with which two magnetic poles act upon one another depends upon the strength of both, we must clearly employ two poles of equal strength. Further, the force with which two magnetic poles act upon one another is greatly affected by the character of the medium between them, that is to say, whether they are acting upon one another through the medium of air or whether they act upon one another through iron, for example. We are obliged, therefore, to adopt some arbitrary standard medium for the transmission of the force. Further, if we take one magnet pole itself, it is invariably associated with another, and in practice if we attempt to influence one magnet pole by any other we are bound to influence the first pole by both poles of the other magnet. We may to a very large extent eliminate the effect of the pole we do not wish to consider by employing an extremely long magnet, so as to remove the pole we do not wish to take into account to a considerable distance from the pole we wish to affect. This elimination will not be thorough, but in the following definition it is supposed to have been completely effected. The unit magnetic pole is defined as a pole of such strength that, when placed *in air* one centimetre away from a precisely equal pole, the force between them, that is with which one acts upon the other, is one dyne. All the other units of magnetism are readily built up from this one in conjunction with the other fundamental units. This unit is, however, the only one which is of immediate interest to us in the formation of electrical units. Both the unit of electrical pressure and the unit of current are based on magnetic units.

---

* This remark applies equally to the definition of velocity just given.

UNIT CURRENT STRENGTH.

If a current pass through a wire placed in the neighbourhood of a magnet, we know that it will affect that magnet by virtue of its own magnetic field to a degree dependent on the current strength. Hence, if we pass a current through a given length of wire, every part of which is at some fixed distance from a magnet pole of known strength, we can take the magnitude of the force exerted by the current on the magnet pole as a measure of current strength. Here again, as in the last unit, we must select some substance arbitrarily as the medium to transmit the force from the current to the magnet, and here again air has been chosen. This brings us to the following definition for the unit of current: Unit current strength shall be such that if it pass through a centimetre of wire every part of which is one centimetre away from a unit magnetic pole it will act upon that magnetic pole with a force of one dyne. Clearly here, if every part of the centimetre of wire is to be at a distance of one centimetre from the magnetic pole, the wire must form an arc of a circle of one centimetre radius, and will subtend an angle of one radian at the centre.

UNIT E.M.F.

The unit of E.M.F. is defined by reference to the cutting of lines of force by a conductor, and therefore before we can proceed to the definition of a unit for this quantity we must define a line of force, or rather we must define the unit for measurement of field strength. This we can readily do with the units which are now at our disposal. If we consider the field strength of a unit magnetic pole, we see that it must necessarily decrease in strength the further one passes away from that pole. Since, however, another unit pole is affected with a force of one dyne *at a distance of one centimetre* from it, it is rational to define unit *field strength* as that strength of field in which, if a unit pole be placed, it will be acted upon with a force of one dyne. We may hence define the unit field in this way, or as the field strength which exists in air at a distance of one centimetre from the unit magnetic pole. All points which are at a distance of one centimetre from such a pole will, of course, form the surface of a sphere of one centimetre radius. We have referred to the measurement of field strength by "lines per square centimetre" on page 193, and unit field must then be represented by one line per square centimetre. We may therefore introduce our notion of magnetic lines by drawing one magnetic line through every square centimetre of surface of that sphere of one centimetre radius. Now a sphere of one centimetre radius has a surface of 4π square centimetres area, so that if there be one line of force to every square centimetre the unit magnetic pole will radiate 4π lines into space. We are now in a position to define the unit of E.M.F. It was pointed out in Section IV. that an E.M.F. magnetically induced may be regarded as being due either to the cutting of lines of force or to the change of lines of force threading a circuit. In both cases, of course, it is the *rate* of the operation which determines the magnitude of the E.M.F. Bearing this in mind, we obviously may define our unit E.M.F. either as that which will be generated by the change of one line per second in the number threading the circuit, or as that which will be due to the cutting of one line per second by a conductor. The Paris definition runs as follows: It is the E.M.F. which will be generated in a conductor one centimetre long moving with a velocity of one centimetre per second at right angles to the lines of a field of one line per square centimetre. The three modes of stating the definition give identical results.

UNIT RESISTANCE.

The third electrical quantity, of the unit of which it is important to have an accurate definition, is resistance. Curiously enough, the abstract conception of the unit of resistance has given rise to considerable difficulty, and has led to considerable enlightenment in an entirely unexpected direction. Both the difficulty, however, and the enlightenment are of a purely scientific nature, and reference to these is therefore relegated to the appendix to this section. For our present purpose we are quite justified in deriving our definition for the unit of resistance direct from those of current and E.M.F., and we may thus define it as that resistance which will permit the unit current to flow under the application of the unit of E.M.F. So much for the definition of what are called the absolute units. They are of enormous importance, but at the same time without further work they would be equally useless. How, for example, could a man in doubt as to the accuracy of his current measuring instrument, or of his electrical pressure measuring instrument, determine whether or not the instrument were accurate unless he were provided with some readier means of verification? The need for this means resulted in the definition of a further set of units, as distinct from those just given, and which are known either as the "Absolute Units," or C.G.S. units.

AMPERE, VOLT AND OHM.

The set of units to which reference is now to be made are known as the "Practical Units." In order to distinguish these units clearly from any of the absolute units which have received names, it was decided that the practical units should all have names derived from the names of eminent men who had contributed to the development of electrical science. Thus the practical unit of current has been called the "ampere"; that of pressure the "volt," after Volta; that of resistance the "ohm," after Professor Ohm; while others mentioned later have received names of similar origin. At the time the definitions of the practical units had to be made, electrical science was in such a state of partial development that by common consent a set of roughly determined units was in use. The unit of E.M.F., for example, commonly taken, was the E.M.F. of a Daniell cell; and that of resistance, the resistance of a mile of iron telegraph wire; following which the unit of current should have been the current which a Daniell cell would have sent through such a wire. In order, therefore, not to introduce units whose magnitude should be very greatly different, that is, should be hundreds of times greater or less than the magnitude of the units in common use, the Paris Congress decided that the practical units should be some integral power of ten times the absolute units. The absolute unit of E.M.F., for example, was so excessively small in comparison with the E.M.F. of a Daniell cell, that had the absolute unit been retained as the practical unit, the E.M.F. of a Daniell cell would have been 107,000,000 volts. It was therefore decided that the volt should be 100,000,000 absolute units in magnitude. The absolute unit of current, on the other hand, was considered so big as to be clumsy, and, unfortunately for us at the present day, the ampere was defined as one-tenth of the absolute unit. Hence, since the ohm must be equal to the volt divided by the ampere, we find that the ohm works out to 1,000,000,000 times as big as the absolute unit of resistance. These three units having been settled upon, the other units only needed naming, since they could very readily be derived from those already determined, provided that the magnitude obtained by direct derivation was suitable for practical purposes.

COULOMB, WATT, JOULE, FARAD, MAXWELL GAUSS AND HENRY.

In point of fact the rest of the units were named on direct derivation: for example, the name "coulomb" was given to the unit of quantity, and it was defined as the quantity conveyed by an ampere in one second ; the "watt," the unit of power, was defined as the power of one ampere at one volt ; the unit of work was called the "joule," and was defined as one watt for one second ; the "farad," the unit of capacity, named after Faraday, was specified as the capacity such that a voltage of one volt would produce a displacement of one coulomb. Since a condenser sufficiently big to have this capacity was almost impracticable to build for direct currents, a subdivision of this unit came into more common use. This subdivision was called the microfarad, and as its name implies, was the one millionth part of a farad. Quite recently an attempt has been made to introduce two further units, or rather to name two of the absolute units which were hitherto unnamed : they are the line of force or flux, and the field strength or intensity of flux. The line of force has been named the "maxwell," and a field strength of one maxwell per square centimetre is known as the "gauss." These units do not appear at the present time to have met with much favour, and it is doubtful indeed whether they ever will do so, seeing that for all practical calculations it would be necessary to speak of a flux of several thousand "kilomaxwells," and densities of 5 to 20 "kilogausses." There yet remains a practical unit of great value for application to circuits which carry a varying or alternating current. It is the unit in terms of which self-induction is expressed (*see* Section VI.). This unit is named the "henry," and represents a self-induction of such magnitude that a current changing in it at the rate of one ampere per second is reacted on by a self-induced pressure of one volt. Such, then, are the units which are in use for practical measurements, and such the basis on which they are founded. For the practical verification of these we have directions for the manufacture of standards for the three fundamental ones, namely, the ampere, the volt and the ohm.

CONCRETE STANDARDS.

In obtaining a practical standard for the verification of our measuring instruments we are of necessity limited to such combinations of materials as lie ready to our hand, it being, of course, an essential that such standards should be constructed with a fair amount of ease and with considerable accuracy at a reasonable cost. In the first place the standard of current strength is perhaps the easiest in this country to reproduce or verify. The law defines the ampere as being a current of such strength that it will deposit silver from a silver nitrate solution at the rate of 0·001118 grams per second. For the accurate verification of current measuring instruments the Board of Trade has issued suggestions and directions, which are embodied in Appendix C.

A standard unit resistance is not so

easily reproduced, nor quite so readily verified. The unit is given by the resistance of a column of pure mercury one millimetre in cross section and 103 centimetres long at a temperature of 0° C.; the weight of mercury in such a column at that temperature should be 14·4521 grams. The verification of standards of E.M.F. is by no means difficult, although the providing of a means of verification certainly demands care. The means which has been for many years in vogue is the E.M.F. of a primary battery known as a Clark cell. It was invented by Mr. Latimer Clark, and consists of a mercury-zinc couple in mercurous and zinc sulphates. The Board of Trade has issued suggestions and elaborate precautions which should be followed in the preparation of a standard Clark cell; these are given on page 59.

Other standard cells have been suggested from time to time, and reference has already been made to the Fleming cell on page 62.

Other cells to give a standard of E.M.F. are those of Weston and Carhart, both of which may really be regarded as modifications of the Clark cell. Particulars of them are as follows :—

CARHART-CLARK CELL.

The objection to the Clark cell, on the score of its high temperature coefficient, has been met by Professor Carhart by the use of a zinc sulphate solution which is concentrated at 0° C.: this results in an E.M.F. of 1·442 volts at 15° C., and is accompanied by a temperature coefficient of 0.039 per cent. per degree C., that of the Clark cell being 0·097 per cent. By using chloride of zinc and mercurous chloride in place of the sulphates, Von Helmholtz obtained a cell whose E.M.F. is about one volt, and may be brought to exactly that value by adjusting the density of the $ZnCl_2$ solution. Carhart has shown the temperature coefficient to be 0·00733 per cent.

WESTON OR CADMIUM CELL.

Weston substitutes cadmium and cadmium sulphate for the zinc and zinc sulphate of the Clark cell. The cadmium is, however, in the form of an amalgam, the proportions of the amalgam having a distinct effect on the E.M.F., a variation of 1 per cent. in the proportion of cadmium giving a corresponding variation of 0·1 per cent. in the E.M.F. Jaeger and Wachsmuth* have shown that with electrolytically prepared cadmium and an amalgam of 1 of Cd to 6 of Hg, the E.M.F. is 1·019 at 20° C., the $CdSO_4$ solution being saturated, that is $3CdSO_4 + 8 H_2O$. The $CdSO_4$ must be carefully neutralised from any trace of free acid. The Hg_2SO_4 paste is made up just as for the Clark cell, only using $CdSO_4$ in place of $ZnSO_4$. Dr. Henderson's form of this very useful cell is shown in Fig. 167. The temperature coefficient is 0·003 per cent. per 1°C.

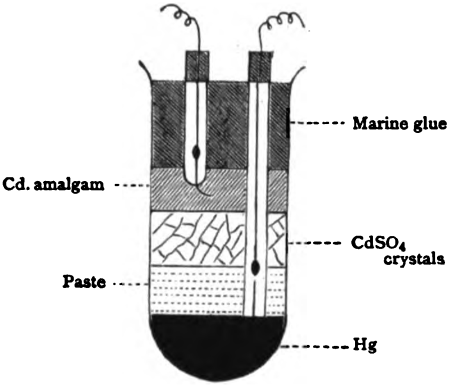


FIG. 167.—CADMIUM STANDARD CELL.

These results, together with the corresponding data referring to the silver chloride cell, are summarised in the table on the following page.

---

* *Wied. Ann.*, Vol. LIX, page 575.

NAME.	ANODE.	CATHODE.	ELECTROLYTES.	E.M.F. AT 15° C.	TEMPERATURE. COEFFICIENT.
Clark	Zinc	Mercury	Zinc Sulphate (sat.) and Mercurous Sulphate	1·434	— 0·079 volt
Carhart-Clark	Zinc	Mercury	Zinc Sulphate (saturated at 0° C.) and Mercurous Sulphate	1.442	— 0·039 volt
Weston	Cadmium	Mercury	Cadmium Sulphate (sat.) and Mercurous Sulphate	1·019	— 0·003%
Von Helmholtz	Zinc	Mercury	Zinc Chloride and Mercurous Chloride	1·0	— 0·0073%
Fleming	Zinc	Copper	Zinc Sulphate 1·4 s.g., Copper Sulphate 1·1 s.g.	1·072	— 0·015 volt
De La Rue	Zinc	Silver Chloride	Ammonium Chloride	1·03	...

THE HEATING EFFECT OF A CURRENT.

With reference now to the heating effect which was described in Section I, we need to determine precisely at what rate heat is generated in an electric circuit. The rate of generation of heat will, of course, depend upon the rate at which work is liberated (that is, upon the power), since it is a universally recognised fact that heat is only one of the numerous forms of work or energy. Now the power in a circuit is represented by the watts, that is, either by the product of amperes, and volts, or what comes to the same thing, by the square of the current multiplied by the resistance. It follows, then, that the rate of heating of a given wire of resistance R is directly proportional to the square of the current strength. For exact work, then, we need nothing further except a factor to change the sign of proportionality into one of quality; that is, we want a coefficient by which when we multiply the square of the current and the resistance together, we shall at once obtain the rate of liberation of heat in terms of some definite unit. The only heat unit to which reference will be made in this book is the C.G.S. calorie, which is the heat needed to raise one gramme of water from 4° to 5° Centigrade.

The amount of work required to produce a given amount of heat, has been determined by various experimenters, notably by Joule, of Manchester, and has been called the mechanical equivalent of heat; most usually, the mechanical equivalent is expressed as the number of foot pounds of work in a British thermal unit, viz. 772·55. For our purpose, however, we shall wish to express this mechanical equivalent in terms of the C.G.S. system, and simply from the relation between the foot and the centimetre, and the pound and the gram, we can from Joule's result find that one calorie is equivalent to forty-one million six hundred thousand dyne-centimetres. Now a dyne-centimetre is a unit of work to which a name has been given; it is called the "erg," and it is, further, the amount of work which is done in moving a conductor a centimetre long and carrying the absolute unit of current (that is, ten amperes) one centimetre across a field of unit strength (one line per square centimetre). If this be done at a velocity of one centimetre per second the operation will last for one second, and the conductor will generate an absolute unit of E.M.F., hence the work done in one second, by an absolute unit of E.M.F. multiplied by an absolute unit of current, is one erg. Since, however, the volt is one hundred million times as big as the absolute unit of pressure, and the ampere is one-tenth as big as the absolute unit of current, it follows that the watt is ten million times as big as one erg per second, hence we say that a watt is equal to 10^7 ergs per second. Now the work done by a watt in one second is a quantity to which another name has been given, namely, the "joule," and it follows from what we have just been saying that one watt-second is equal to one joule, and therefore one joule is equal to 10^7 ergs. From the mechanical equivalent of heat it has been determined that one calorie is equal to 41·6 million ergs, and it thus follows that if we divide the number of watts that are being expended in a circuit in heating it by 4·16 we shall obtain the number of calories that are being liberated per second, or if we wish to know the total amount of heat in calories liberated in a given time, all we have to do is to multiply the watts by 0·24 and by the time in seconds. We can thus easily determine say, the cost of heating a quart of water in an electric kettle, if we may assume that no heat is lost by the kettle to the surrounding atmosphere. This loss, however, always occurs, and will have to be allowed for in arriving at a final conclusion. A quart of water weighs two and a half pounds, or just over a kilogram, namely 1·13 thousand grams. The water is put into the kettle, let us say, at 15° Centigrade (59° Fahrenheit); it will, therefore, have to be raised 85° Centigrade in order to bring it to the temperature of boiling water. If we desire to make it actually boil we shall have to take into account the latent heat of steam and the rate of liberation of steam; we will therefore assume that we only need to bring it up to a temperature of 95° Centigrade, thus requiring a rise of 80°. We now need

$$80 \times 1{,}130 \times 4{\cdot}16 \text{ joules.}$$

This will mean the same number of watt seconds, and if the current is supplied at two hundred volts, we need

$$\frac{80 \times 1{,}130 \times 4{\cdot}16}{200} = 1{,}890 \text{ ampere-secs.}$$

If we wish to heat the water in four hundred seconds—that is, in just under seven minutes—we shall require

$$1{,}890 \div 400 = 4{\cdot}725 \text{ amps.}$$

We may, however, have the problem presented to us in a different form. For example, it may be desired to know what must be the resistance employed in an electric kettle or an electric hot plate in order to give out heat at a certain rate. Since we are only given the E.M.F. and required to state the resistance R, it is well to remember that the power absorbed in a given resistance R supplied at a voltage E is equal to $\frac{E^2}{R}$. Here, then, our calculation is made as follows:

$$H = \frac{E^2}{R} \times 0{\cdot}24,$$

where H = the heat required in calories per second.

CHAPTER II.—GALVANOMETERS.

TANGENT—ASTATIC—DIFFERENTIAL—REFLECTING—THOMSON FOUR-COIL—BALLISTIC —THE D'ARSONVAL—ELECTROMETERS.

PROPERLY speaking, a galvanometer is an instrument for measuring current, and hence under the heading Galvanometer should be included all instruments which are employed for measuring current. As a matter of practice, however, the term galvanometer is not applied to those instruments whose scales are so marked that the indications are read directly in amperes, and, following this custom, only those instruments which are ordinarily called galvanometers will be included under this heading.

The simplest form of galvanometer in use is that known as the Linesman's Detector, and as its name implies, this instrument is hardly used strictly as a galvanometer. Being used as a detector it clearly should be classed as a galvanoscope. It will serve, however, as a rough galvanometer, and may therefore be properly described under this heading. It is illustrated in Figs. 168 and 169. The coil is made in two halves to allow the needle to be pivoted, the two halves being marked C_1, C_2 in the illustration. The needle is of bright steel and of the familiar lozenge shape, except that one end is left blunt to make it heavier, and so provide a gravity control. The pointer seen in Fig. 168 is also a magnet, the two being arranged astatically (*see* page 248). Each coil carries two distinct windings, one of thick wire and few turns, the other of thin wire and many turns. The middle terminal is common to both windings.

TANGENT GALVANOMETER.

Another exceedingly simple galvanometer is that known as the tangent galvanometer. For simplicity of construction it certainly cannot be excelled, even by the Linesman's Detector, while it differs greatly from the former in that it can be used as an instrument of great precision. A tangent galvanometer consists of a circular coil whose plane when the galvanometer is in use is set carefully parallel to that of the magnetic meridian. If a current be sent round the coil the field which it produces at its centre is in a direction at right angles to the direction of the earth's magnetic field. At this point, therefore, we have two forces acting

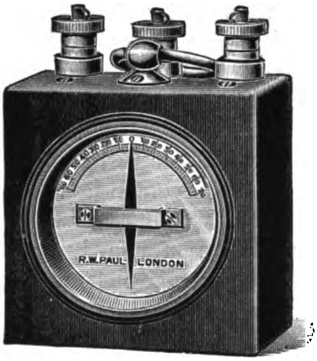


FIG. 168.—LINESMAN'S DETECTOR.

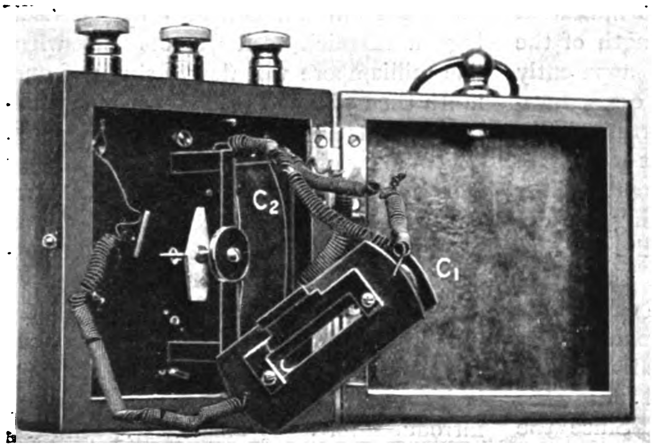


FIG. 169.—INTERIOR OF LINESMAN'S DETECTOR ; ONE HALF-COIL C1 REMOVED DISCLOSING NEEDLE.

at right angles to one another, and their resultant can be determined by a simple parallelogram of forces in the well-known way as indicated in Fig. 170. Clearly the direction of this resultant will depend entirely upon the relation between the magnitude or strength of the field produced by the coil and the strength of the field due to the earth. Hence varying currents in the coil will, in combination with that of the earth, produce resultant fields of varying direction and strength. At the centre of the coil a small dumpy needle is either suspended or pivoted so as to move about a vertical axis. This needle acts simply as a weather vane—that is to say, its function is not to measure the strength of the magnetic field produced,[*] but its direction, just as a weather vane merely indicates the direction in which the wind is blowing, but not its force. The direction of the resultant field at the centre of the coil depends, however, on the strength of the field which the coil superposes upon that of the earth, and hence the direction of the resultant is an indirect measure of the strength of the component provided by the coil. It is easily seen that the direction of the resultant is such that the tangent of the angle θ is proportional to the coil field, and therefore to the current, provided the earth's field is constant and perpendicular to the plane of the coil. The direction of the magnetic axis of the dumpy needle is made clearly visible by attaching a long slender pointer to the needle, usually at right angles to its magnetic axis. When so attached the end of the pointer is at zero when the pointer lies in the axis of the coil, and hence is easily seen, and it will not lie in the plane of the coil unless the deflection of the needle reaches 90°. One great advantage of the tangent galvanometer is that if the dimensions of the coil be accurately known and the strength of the earth's field at the place where it is used be also known, its indications may be predetermined with very great accuracy. Moreover, when once the coil has been built and the earth's field is known, no change in the magnetism of the needle will affect the accuracy of the readings, nor are there any springs, weights, or controlling magnetic fields to suffer change and introduce variation. The only varia-

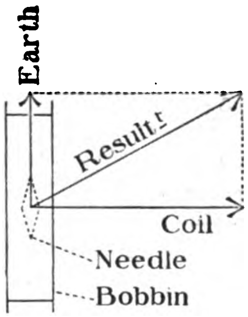


FIG. 170.—DIAGRAM OF FORCES AT WORK AND POSITION OF PARTS IN TANGENT GALVANOMETER, BEFORE DEFLECTION TAKES PLACE.

---

[*] If the controlling field and that due to the coil were both doubled, the field produced would be double, but the deflection on the galvanometer unchanged.

tion liable to interfere with the indication of the instrument is in the strength of the earth's field (or of the field apparently due to the earth). In most cases, however, the field due to the earth may be determined in a laboratory, at least with considerable accuracy, by magnetometer methods (*see* Chap. VI.). Failing the determination of the earth's field the galvanometer may be calibrated at some one point of its scale by an electrolytic method or in any other convenient way, and its constant so determined will hold good all over the scale and until the earth's field again changes. Since the indications of the instrument so depend upon the earth's field, it is clearly of the utmost importance to shield a tangent galvanometer from the presence of any stray magnetic fields such as would result from the near neighbourhood of dynamo machines, etc., or permanent magnets, or even from the wires bringing up the current to the galvanometer: these should always be twisted together, so that one neutralises the effect of the other.

A rather useful form of tangent galvanometer has for very many years been known as the Post Office type. The convenience of this form lies in the fact that its resistance just permits one one-thousandth of an ampere to flow when an ordinary Daniell cell is connected across its terminals. The resistance of the Daniell cell, no matter how badly made up, is usually quite incomparable with that of the fine wire coil. The instrument thus may readily be calibrated in milliamperes by connecting a Daniell cell across it, when one milliampere will flow, a shunt of one-ninth then giving a ready means for reading currents up to about 50 milliamperes. The number of turns wound upon the other coils is also known, and hence, if the difference in the mean diameters of the several windings be negligibly small, the indications of the instrument when currents are sent through the various windings may readily be deduced. If measurements are taken of the diameters while the instrument is being made, corrections may easily be introduced for these differences. The circuits of the main part of the instrument are shown in Fig. 171, there being two plugs which may be inserted in the sockets A, B, C as desired.

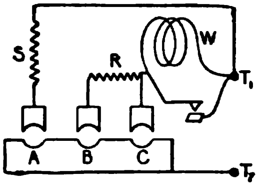


FIG. 171.—POST OFFICE TANGENT GALVANOMETER; W, COIL OF FINE WIRE, 320 OHMS; R, EXTRA RESISTANCE 750 OHMS; S, SHUNT OF 118·9 OHMS; T_1, T_2, TERMINALS; A, B, C, PLUG SOCKETS.

It follows from what has been said on page 194, that the strength of field due to the coil is $\frac{2 \pi r C}{r^2}$ if r is the radius of the coil in centimetres and C the current strength in C.G.S. units. If we write H for the strength of the earth's field (horizontal component) then

$$\tan \theta = \frac{2 \pi C}{r} \div H,$$

$$\text{whence } C = \tan \theta \frac{H r}{2 \pi}$$

or if the current be A amperes and there are n turns on the coil,

$$A = 10 \tan \theta \frac{H r}{2 \pi n}$$

ASTATIC GALVANOMETER.

The tangent galvanometer is controlled by the earth's field, while the Linesman's Detector, described on page 244, has what is known as a gravity control; that is to say, the force tending to return the needle to zero, instead of being the earth's field, is the force of gravity, the needle being, of course, suitably loaded at one end. If we desire to obtain a greater sensitiveness in any of the instruments described, it can only be attained by increasing the number of turns of the windings, and in this direction, of course, a limit is soon reached. It is useless in the tangent galvanometer to expect greater sensitiveness by employing a needle of greater magnetic strength, for the reasons already given. It may act more promptly, but the indication which it gives will be the same no matter what its strength. The only way, then, to attain a higher sensitiveness of such instruments is to reduce the controlling effect of the earth's field. This has been achieved by combining together two magnets in such a way that the controlling effect of the earth upon one of them is partially or entirely neutralised by the control exerted on the other. Such a combination is called an astatic combination, it being truly astatic when the magnetic moment of one of the magnets is precisely equal to that of the other. In such a case the pair, considered as a whole, does not experience any controlling force whatever from the earth's field. They may be arranged as shown in Fig. 174 (*a*). It is, however, as a rule, impossible to provide two magnets of precisely equal magnetic moment, and in that case we get two magnets of approximately equal magnetic moment, with the result that the directive action of the earth is slightly stronger upon one of them than on the other; and hence the total directive action is very weak, being only the difference between the two. The two magnets so combined can then be employed so as to obtain a very sensitive instrument if the coil encloses and acts upon only one magnet; but the sensitiveness obtained may be enhanced by so arranging the coils of the galvanometer that while the earth's directive action on the combination is the

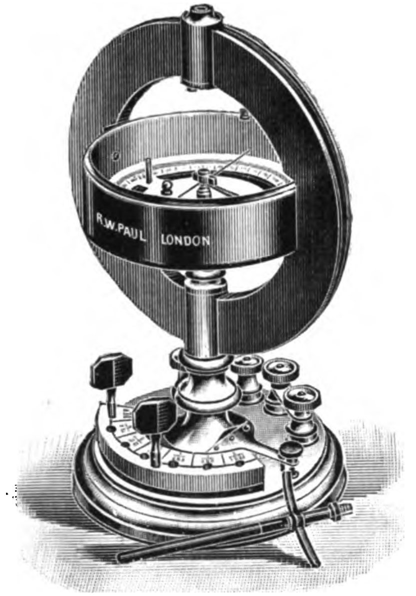


FIG. 172.—POST OFFICE PATTERN TANGENT GALVANOMETER.

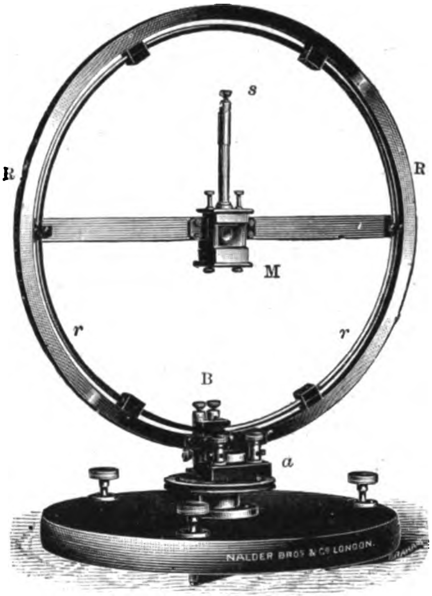


FIG. 173.—STANDARD TANGENT GALVANOMETER; R, R, CHANNELLED RING CARRYING COIL OF MANY TURNS; *r*, *r*, COIL OF ONE TURN OF BARE COPPER; M, MAGNET BOX HOLDING MIRROR AND MAGNETS SUSPENDED FROM *s*; *a* AND B, TERMINALS TO COILS IN R AND TO COIL *r* RESPECTIVELY.

difference of its effects on the two magnets, the total directive action due to the coils is the *sum* of their action on the two. This is brought about by placing the combination with one magnet inside a coil while the other is close to it, but outside. Here clearly, the outside magnet is affected by the return flux which has passed through the coil in one direction and returns outside the coil in the opposite direction; only a portion, however, of the total flux threading the coil returns past the outside magnet, and if further sensitiveness is wanted, a third magnet might be added on the outside, having its poles pointing in the same direction as those of the other outside magnet. If this were done, however, the two outer magnets would each have to have approximately one-half the magnetic moment of the inside magnet. An astatic galvanometer of this kind can be made very sensitive even if the movement be mounted on jewelled pivots instead of being suspended by a fibre. Such a construction provides us with a portable instru ment of considerable sensitiveness, though, of course, not equal to an instrument having a silken suspension, since the pivot friction reduces the sensitiveness.

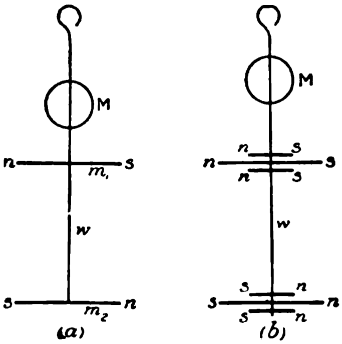


FIG. 174.—ASTATIC COMBINATIONS; (*a*) WITH TWO MAGNETS, m_1 AND m_2; (*b*) WITH SIX MAGNETS; M, MIRRORS; *w*, CARRYING WIRE.

THE DIFFERENTIAL GALVANOMETER.

An astatic instrument, such as has been described, lends itself very readily to the construction of a differential galvanometer, In such an instrument the coil is made in two halves, the winding of each coil being brought out to two independent terminals. The instrument will then serve to indicate, if it be properly adjusted, whether two currents are of equal strength or not. One of the currents is taken through one half of the coil and the other current, to be compared with it, is taken through the other half coil. The connections must be made so that the magnetic effect of the current in the one coil opposes that of the current in the other, and if the instrument be in adjustment the needle will experience no deflecting force when the two currents are equal. In order to see whether the instrument is in adjustment, all that is necessary is to connect the two coils in series and to send a current through them. Then, since the same current is flowing through both coils, if the needle deflects in either direction the instrument is out of adjustment. Since great care is exercised in the manufacture to put precisely the same number of turns on to each coil, and as

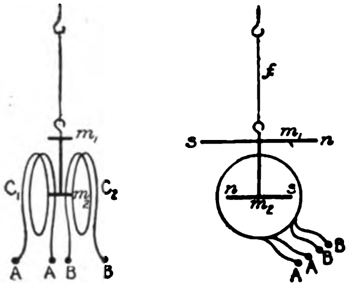


FIG. 175.—DIAGRAMS ILLUSTRATING PRINCIPLE OF DIFFERENTIAL GALVANOMETER; A, A, TERMINALS OF COIL C_1; B, B, TERMINALS OF COIL C_2; m_1, m_2, ASTATIC PAIR OF MAGNETS; *f*, SUSPENDING SILKEN FIBRE.

nearly as possible in symmetrical positions on the bobbins, the only want of adjustment that can occur after the instrument has once been made is in the position of the magnets relatively to the coils; that is to say, if one coil does have a predominating influence over the magnet when the test is applied, it is almost certainly because the magnet is slightly nearer to that coil than to the other. Hence correction is obtained by altering the position of the needle relatively to the coils, which can generally be readily effected by careful levelling. Whenever any testing has to be done by means of a differential galvanometer it is of the utmost importance that the instrument should be tested in the way just described, before proceeding to make any measurements with it. For some of the uses of this instrument the reader is referred to the pages dealing with the measurement of resistance.

REFLECTING GALVANOMETERS.

The preceding instruments have been described as provided with a pointer of some kind to enable the small rotational movements of the magnetic system to be readily observed. The weight of these pointers is, however, a distinct disadvantage, since it makes a delicate suspension more difficult, and greatly increases the moment of inertia of the moving parts. The increase, too, is greater the longer the pointer, and yet the longer the pointer the more accurately can the indications be read. Hence, while we desire to make the pointers extremely long we are prevented from doing so owing to their weight. The trouble could be quite got over if we could find a material which would have no weight for pointers, for even aluminium possesses sufficient mass to be quite objectionable for pointers more than about 4 in. or 5 in. in length. Fortunately we have a means of providing what is virtually a pointer which has no weight whatever. The magnetic system is provided with a small concave mirror which may be about three-eighths of an inch in diameter and exceedingly light. If a beam of light be sent from a lamp through a double convex lens, so as to throw a sharp image of the flame on the mirror, the mirror will reflect the beam, so that, if intercepted upon a screen at the right distance from the mirror, it will give a sharply defined round spot of light. If the source of light be placed slightly below the level of the mirror and opposite to it when the needle is at rest, the reflected beam from the mirror will throw a spot just over the source of light if a screen be put there to intercept it.

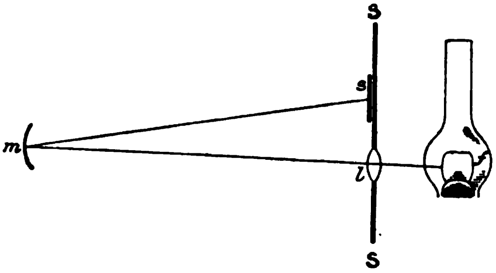


FIG. 176.—DIAGRAM SHOWING ARRANGEMENT OF LAMP FLAME, *f*; LENS, *l*; CONCAVE MIRROR, *m*; SCALE, *s*; AND SCREEN, S S.

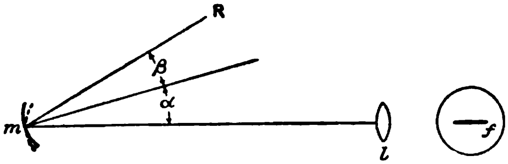


FIG 177.—DIAGRAM SHEWING RELATIVE ANGULAR DISPLACEMENT OF MIRROR AND REFLECTED BEAM:—*m*, MIRROR; α, ANGLE OF MOVEMENT OF MIRROR; R, REFLECTED BEAM; $\alpha + \beta = 2\alpha$.

If, now, the needle be deflected, the beam from the lamp no longer falls normally on the mirror, but at an angle equal to the angle through which the mirror has been rotated, and since the angle of reflection is equal to the angle of incidence, the reflected beam will make, with the beam from the lamp, an angle equal to twice that through which the mirror has been deflected. Now a beam of light weighs nothing, and we can make a pointer of light just as long as we please, so long as we can get a sufficiently intense source of light. It is common in reflecting galvanometers to put the source of light and the screen both at the same distance from the galvanometer, and to make that distance about a yard, although for really delicate work the scale is often placed as much as six feet from the mirror. Of course, the mirror on the needle is only suited to one particular distance from the scale, and hence it is necessary to change the mirror if it be desired to work with the scale at twice the distance from the instrument, unless the lamp be left at about three feet and the scale be moved separately. In order further to give accuracy in reading, the collimating lens in front of the lamp is provided with a scratch along a vertical diameter, or a wire is stretched over it. This scratch or wire will then show a vertical black line in the bright spot which is intercepted upon the scale and readings can be taken of the movement of this black line on the scale. With this arrangement minute deflections can very readily be measured, as will at once be perceived when we consider that the angular motion of the reflected beam is double that of the needle; since a movement of the spot of light of half a centimetre may be quite accurately read, it follows that an angular movement of the needle, of 0·142°, to which this corresponds at a scale distance of one metre, is read with accuracy.

The most sensitive reflecting galvanometers having suspended magnets are of the type known as the

THOMSON FOUR-COIL GALVANOMETER,

invented many years ago by Lord Kelvin, then Professor William Thomson. The Thomson four coil is an astatic reflecting galvanometer, provided with four coils so combined as to virtually form two. The coils, however, are always wound on four separate bobbins, and hence are always regarded as four separate coils. The coils are arranged as shown in Fig. 179, the upper pair enclosing the upper magnets of the astatic combination, and the lower pair enclosing the lower magnets. The upper magnet is replaced by several smaller magnets, generally about five in number, these being secured to the back of the mirror as is shown in Fig. 178. All these little magnets have their poles, of course, point-

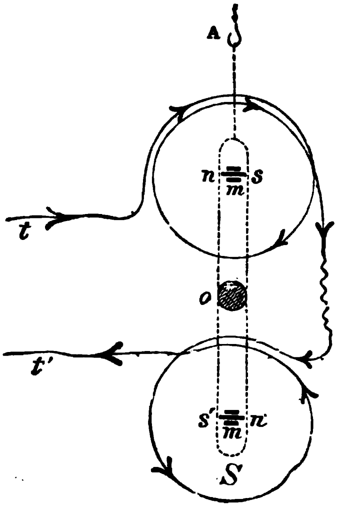


FIG. 178.—DIAGRAM OF WINDINGS AND MAGNET SUSPENSION OF THOMSON FOUR-COIL GALVANOMETER. A, SUSPENDING HOOK; *t*, *t′*, WIRE TO INDICATE DIRECTION OF WINDINGS; *o*, MIRROR; *m*, MAGNETS.

ing the same way. The use of a number of small magnets in this way is found to give greater strength for a given weight than one larger magnet. They are made of hard thin watch spring. The lower magnets are similarly arranged, and are attached to the lower end of a light wire, which also carries the upper magnets with the mirror. To the lower side is also sometimes attached a light aluminium or mica vane; but this is only permissible when the instrument is not to be used ballistically, the function of the vane being to damp the oscillations of the needle by the eddy currents which it sets up in the air. The back coils of the upper and lower pair are usually mounted in a vertical brass plate which is fixed to the base of the instrument, the front pair being carried by a similar plate which is hinged to the fixed one. The magnetic system is suspended from a point of support on the fixed brass plate, and hence, when the front plate is swung about its hinges, the suspended system is clearly exposed to view, and is readily accessible for adjustment or repair.

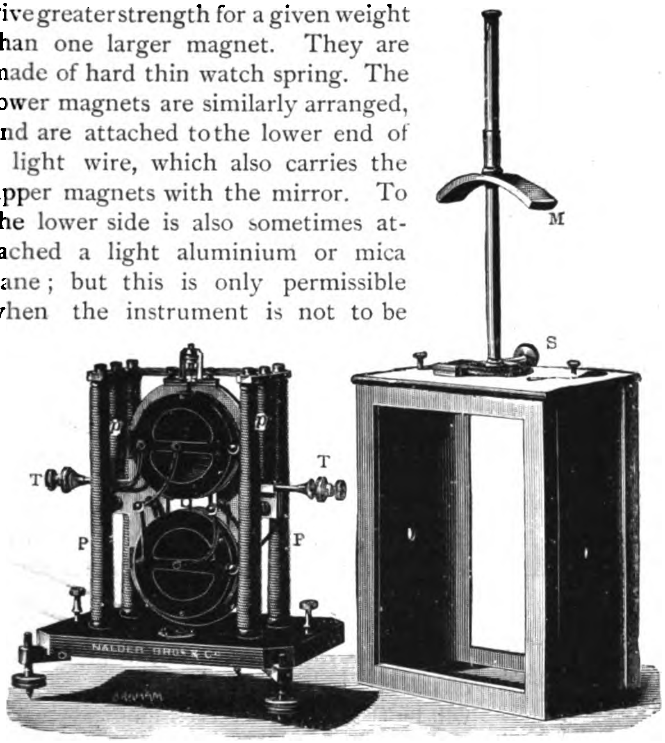


FIG. 179.—SENSITIVE FOUR-COIL THOMSON GALVANOMETER, CASE REMOVED. P, CORRUGATED EBONITE PILLARS SUPPORTING COILS; T, TERMINALS CARRIED BY PILLARS, *p*; M, CONTROLLING MAGNET; S, TANGENT SCREW FOR ADJUSTING M.

The coils and the terminals are very carefully insulated by being supported on corrugated ebonite pillars. Currents of the order of 6×10^{-10} amperes can be measured with an instrument of this kind having a resistance of 15,000 ohms. The sensitiveness depends, of course, on the strength of control exerted by the magnet M, and as the period of swing depends also on this, it is usual to specify the sensitiveness when the swing has a certain period, and when, therefore, the magnet M is at a definite height. Thus a certain galvanometer of Elliott's of 40,000 ohms, has a sensitiveness of 6×10^{-13} amperes per millimetre, at a scale distance of one metre and with a period of 11 seconds. The period, or slowness of swing, is a measure of the weakness of the control, and hence of the sensibility. The period is measured by the number of seconds needed by the needle to make one complete swing to and fro.

BALLISTIC GALVANOMETERS.

The ballistic use of a galvanometer will best be understood by recalling the fact that its name is derived from the old Roman battering-ram or ballista. The use of the instrument is similar electrically to the mechanical use of the ballistic pendulum in the measurement of the velocity of rifle bullets, and a brief description of this will further help to an understanding of the electrical case. It was the practice at one time to measure the velocity of rifle bullets by firing them into a massive block of metal faced with wood, and suspended by an exceedingly long suspension, so as to be free to swing as a pendulum. The bullet was fired into the wooden face and stopped by the metal at the back, remaining embedded in the pendulum. The latter, owing to its exceedingly long suspension, had a very slow natural period of oscillation, and owing to the great mass of the block as compared with that of the rifle bullet, the former virtually did not commence to move in its forward swing until the rifle bullet had been brought to absolute rest. When this was the case, the whole of the energy of the bullet was delivered to the block (with its embedded bullet), resulting in a force acting in one direction only, namely, horizontally. The amount of this delivered energy was then measured by carefully observing the magnitude of the first swing of the pendulum. Had the pendulum been constructed with a quicker period of vibration, or with a less mass it would have begun its forward movement and have executed an appreciable portion of it before the bullet had been brought to rest, and thus, as will be seen from the diagram in Fig. 180, the portions of energy last delivered would have exerted forces of which components only would have been acting at right angles to the suspension; hence one might say that these portions of energy would not have had as good a chance to augment the deflection as those which were first delivered, and which produced forces acting wholly at right angles to the suspension. It follows, then, that the essentials for a good ballistic pendulum are slow period and large moment of inertia, so that the whole of the energy to be measured shall be delivered under the same conditions. Electrically this is effected by providing the galvanometer with a movable portion which has a high moment of inertia and a very slow period of oscillation. If, then, an instantaneous current be sent through the coils of the galvanometer we may say that to all intents and purposes the current will have died out and will have imparted the whole of its impulse to the moving portion before the latter starts from rest; thus the whole of the impulse will have been delivered under equally favourable conditions, and the magnitude of the first swing of the suspended system will be the principal measure of the energy delivered. Any galvanometer, then, which fulfils these requirements may be used as a ballistic galvanometer; but while this is so, it will be readily appreciated that instruments so constructed are particularly unsuited for use in the ordinary way, and it is hence customary to describe galvanometers particularly designed for ballistic use as ballistic galvanometers, although, of course, they may be used in any other way desired; that is to say, to produce permanent deflections instead of mere swings. It also follows that since the swings are to be measured it is necessary that there shall be as little frictional retardation as possible, for the magnitude of the first swing will in that case not be proportional strictly to the energy delivered; hence anything on the suspended portion which is likely to set up air

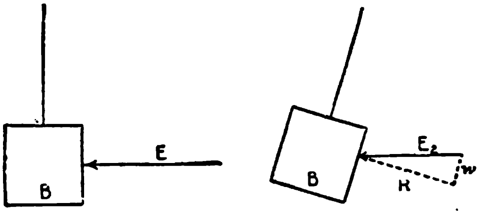


FIG. 180.—DIAGRAM OF BALLISTIC PENDULUM B. E, DIRECTION OF MOVEMENT OF BODY GIVING ENERGY TO B; R, USEFUL COMPONENT; *w*, COMPONENT WASTED WHEN PORTION OF ENERGY HAS TO BE DELIVERED ALONG E_2 AFTER B HAS MOVED.

currents must be carefully avoided, and so also must any design or construction which would tend to set up eddy currents, for these would have a retarding effect which would entirely prevent any true proportionality. This freedom from frictional retardation renders the galvanometers very unsuitable for producing permanent deflections, since they are so exceedingly slow in coming to rest even in the deflected position; and they are no less tedious for use ballistically, since they are equally slow in coming to rest in the zero position, and a deflection cannot be taken until they are absolutely at rest. Now although by careful construction frictional retardation, or damping as it is ordinarily called, may be reduced to a very small thing, it is invariably present to some degree, and must therefore be taken account of for accurate work. Its presence means that the magnitude of the first swing (and, indeed, of all succeeding ones) is less than it would have been had there been no damping; and to correct for it, observations have to be taken on the instrument in the following way: The needle is set swinging; this may be done in various ways. A transitory current may be sent through it or a permanent deflection may be produced, and the circuit then be suddenly broken; but in either case the successive swings right and left of the middle point must be carefully noted. These readings are then plotted on a curve on the assumption that they occupy equal durations of time, time being plotted horizontally and the magnitudes of the deflections vertically. This produces a curve of the kind illustrated in Fig. 181. The crests of the ripples are of continually decreasing height, and when joined together give the dotted curve which is known as a logarithmic curve. It will be seen from this that the bigger the deflection the greater the amount of damping; hence for very large deflections the damping very seriously impairs the accuracy of the method. The correction is explained in Chapter V.

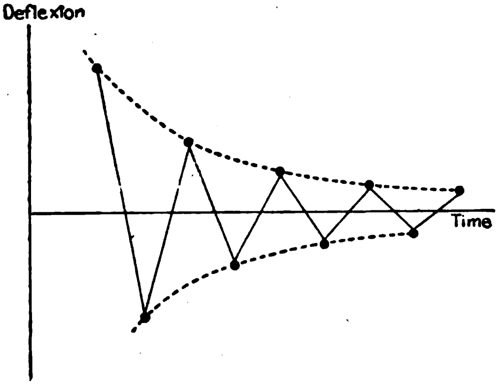


FIG. 181.—CURVE OF LOGARITHMIC DECREMENT OF BALLISTIC GALVANOMETER.

THE D'ARSONVAL GALVONOMETER.

This form of galvanometer was originally devised by D'Arsonval, but was for a long time very inferior in sensitiveness to the best forms of suspended magnet galvanometer. Of late years, however,

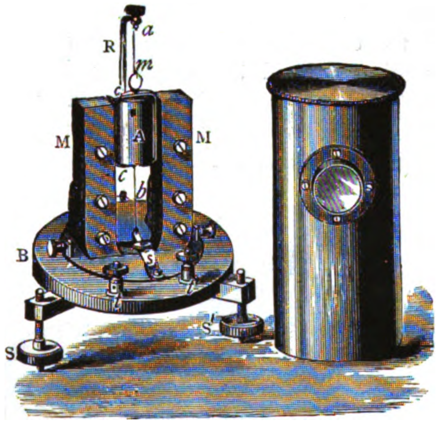


FIG. 182.—D'ARSONVAL GALVANOMETER; M, PERMANENT STEEL MAGNET; A, IRON CORE; *c*, MOVING COIL SUSPENDED BETWEEN FIXED POINT *a* AND SPRING *s*; *m*, MIRROR.

owing to the great amount of attention given to it and skill employed in the design, D'Arsonval galvanometers of extraordinary sensitiveness have been produced by several makers, prominent among them being the Ayrton-Mather form, made by Paul; the Holden form, made by Pitkin; and the Crompton form, made by Messrs. Crompton. In the D'Arsonval galvanometer the functions of the fixed and moving parts are reversed, as compared with the Thomson form. In the D'Arsonval galvanometer it is the magnet that stands still and the coil that is deflected. The magnet is a very powerful permanent magnet of horseshoe type, though not necessarily exactly a horse shoe in shape, and with one exception all the forms of D'Arsonval galvanometer have an iron core placed midway between the poles. The coil to which the mirror is attached is suspended so as to embrace this core without touching it, and the wires forming two sides of the coil consequently lie in the two gaps between the magnet poles and the core.

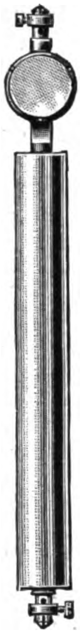


FIG. 184.—TUBE CONTAINING COIL AND CARRYING MIRROR FOR AYRTON-MATHER D'ARSONVAL GALVANOMETER.

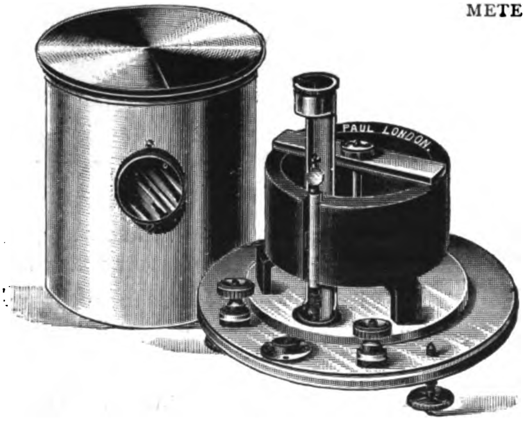


FIG. 183.—AYRTON-MATHER FORM OF D'ARSONVAL GALVANOMETER.

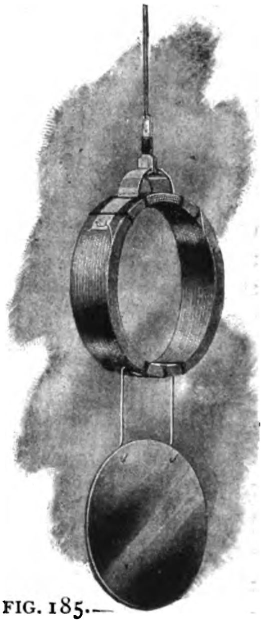


FIG. 185.—COIL AND MIRROR OF CROMPTON D'ARSONVAL GALVANOMETER.

The exception referred to is the Ayrton - Mather galvanometer, in which the poles are made to approach one another much more closely than in other forms, and the coil is a long, very narrow one, lying in the gap between the poles. In all D'Arsonval galvanometers the connection to the coil must be metallic, since the current to be measured has to be introduced into the moving coil. In the older forms current was led in through a fine hair-like strip of phosphor bronze attached to the top of the coil and connected to one end of the wire forming the coil. The other end of the wire was connected to another phosphor bronze strip attached by one end to the bottom of the coil, and by its other end to a very light flat spring (*see* Fig. 184). The tension of this spring kept the two phosphor bronze strips taut, and the coil was thus held suspended between a fixed point to which the top end of the upper strip was secured, and the end of the brass spring to which the bottom end of the lower strip was secured. The position of the coil when no current is passing is controlled by the phosphor bronze strip, which, owing to the tension in it, tends to untwist until it is perfectly flat. On the other hand, if a current is sent through the coil (which the strips tend to keep with its plane parallel to the lines of the magnetic field) it will tend to swing round so that its own field coincides with that of the field in which it lies, and in so swinging twists up the phosphor bronze strip, shortening it to a minute degree and increasing the tension in it to a corresponding degree. Thus the force of deflection rotates the coil until it is balanced by the force of restitution due to the twisting of the phosphor bronze strips, then, when this is attained, a steady deflection results. The pre-eminent characteristic of a D'Arsonval galvanometer is the enormous damping action which is easily obtained by winding the coil on a bobbin of silver or copper. So soon as the coil moves the bobbin becomes the seat of eddy currents set up by its movement in the magnetic field of the permanent magnet. These eddy currents are, of course, proportional to the speed of movement of the bobbin, and hence act more powerfully the more violent the impulse given to the coil, and also cease to act when the movement of the coil ceases. They thus provide a most perfect damping arrangement which makes work with a modern D'Arsonval galvanometer a pleasure, and it is not too much to say that measurements involving steady deflections can be taken with a D'Arsonval galvanometer in from one-sixth to one-tenth the time needed with the most skilful use of a Thompson four coil. For ballistic work D'Arsonval galvanometers were for a long time unsuited, owing to the very great difficulty of obtaining material for the coil and its parts entirely free from magnetic matter. It is surprising at first to learn that such

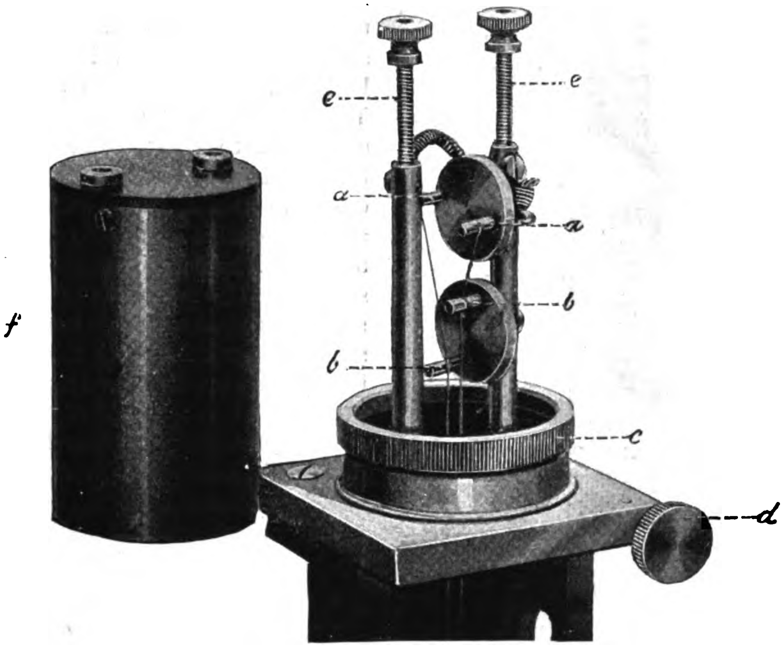


FIG. 186.—THE BIFILAR ADJUSTMENT HEAD OF CROMPTON'S GALVANOMETER.

things as ebonite, copper, silk, etc., possess, as a rule, sufficient traces of magnetic material to render them quite unsuitable for really delicate ballistic work in D'Arsonval galvanometers. This is, however, the case, and it is only by dint of the most careful selection and testing of materials, and scrupulous care in manufacture, that truly ballistic D'Arsonval galvanometers can be turned out.

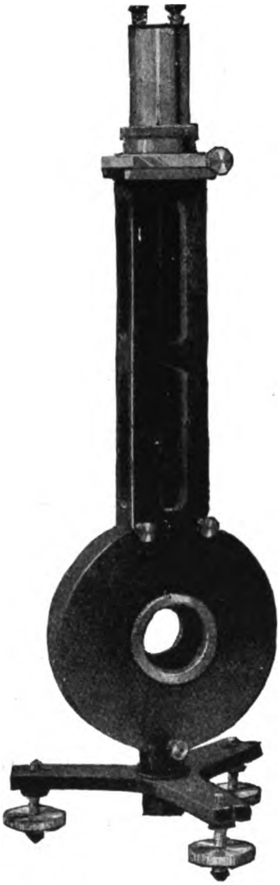


FIG. 187.—CROMPTON'S BIFILAR D'ARSONVAL GALVANOMETER.

An interesting form of D'Arsonval galvanometer is that brought out by Messrs. Crompton. The main point of difference in this instrument from those already described is that the suspension is bifilar, the coil being suspended by two extremely fine phosphor bronze strips from two insulated terminals in the head of the instrument. The two strips are connected at their lower ends to a sort of inverted T-shaped carrier, which is seen clearly in Fig. 185, the two lateral branches of the T being insulated from one another and connected to their respective phosphor bronze strips. The coil, which is cylindrical in shape, is provided with two arched metallic strips, forming a sort of open claw, which just slides on to the T support. The two ends of the coil winding are connected to these two arched strips respectively, so that when the claw is slipped over the inverted T, circuit is made from one terminal of the instrument down a phosphor bronze strip and its limb of the T piece, through one arch of the claw, round the windings of the coil, out by the other arch and its limb of the T, up the other phosphor bronze strip to the second terminal of the instrument. This provides for a very ready replacement of the coil, all that is necessary being to remove the front of the instrument, slip one coil off the T and slip on another. A very large mirror is employed, which is seen in Fig. 185, depending from the coil by two hooked wire supports. In the best type of this instrument adjustment is provided for sensitiveness by varying the distance apart of the two points at the top of the bifilar suspension. These are seen in Fig. 186, which is an enlarged view of the head of the instrument, the latter being shown complete in Fig. 187. The two phosphor bronze strips are attached to two fixed pins *a*, *a*, whose position determines the maximum distance apart at which the ends of the strips can be. Two grooved pins *b*, *b*, are provided on a lower disc, which is held friction-tight on one of the supporting pillars, and the rotation of this disc about its axis affords a means of adjustment of the distance apart of the strips. The whole head seen carrying the two supporting pillars and terminals, *e*, can be rotated in a sleeve which holds it friction-tight, while a tangent screw, *d*, provides for a fine adjustment of the sleeve, and so of the whole head and suspension, thus affording an excellent zero adjustment.

The bifilar suspension clearly lends itself admirably to differential winding, since a third connection common to both windings may be provided at the lower end of the coil, as in the ordinary type of D'Arsonval. The great obstacle, however, in the way of the manufacture of these instruments lies in the difficulty of insulating the two windings one from the other sufficiently well for fine work. It is not difficult, of course, to insulate them after a sort, but if the instrument is to be really useful the insulation must be sufficiently good to prevent any leakage great enough to modify the deflection. Although this can be done, and is done, the instruments do not appear to have any particular features of value beyond those of the ordinary moving magnet type.

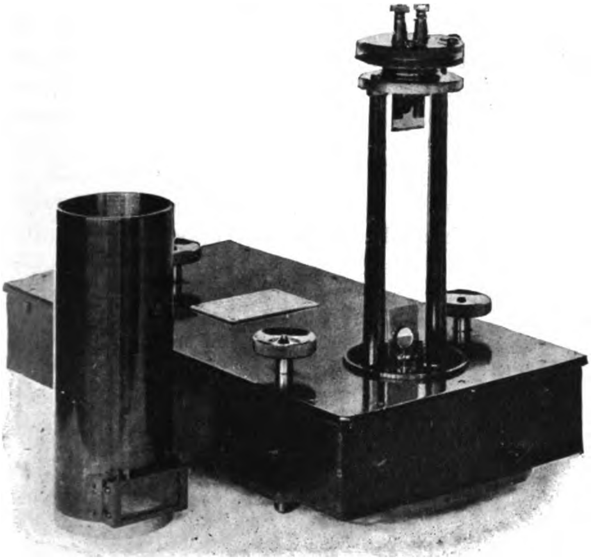


FIG. 188.—CAMPBELL'S FORM OF D'ARSONVAL GALVANOMETER FOR STANDARDISING WORK.

Instruments in which the control consists largely or entirely of the torsion in the phosphor bronze suspending strips are very liable to have a creeping of the reading on continuous deflection for a long period, together with the uncertainty of return to zero, due to fatigue, or elastic set in the spring control. This has been entirely obviated by the form of suspension adopted in the galvanometer designed by Mr. Albert Campbell (Fig. 188) and made by Mr. Paul, and the zero error which occurs to a greater or less extent in sensitive instruments of this type, due to the presence of minute quantities of magnetic material in the coil, has been entirely eliminated by the adoption of comparatively large forces which results, however, in a comparatively low sensitiveness. The permanent magnet measures about 13 in. × 7 in. × 2 in., and is provided with a permanently fixed cylindrical core, the field of the instrument being about 2,000 C.G.S. lines per square centimetre, thus providing efficient damping for the coil, which is wound on a metallic former.

For current measurements, with external shunts, a coil is wound with eighty turns of wire, having a resistance of about 9 ohms, the resistance of the instrument, including the suspension wire of ·003 in. phosphor bronze, being about 12 ohms.

The deflection given by one milliampere, at a scale distance of one metre, is about 800 millimetres, the distance apart of the bifilar wires being 13 millimetres. This distance may be varied if required to produce different sensibilities. With the above adjustment, the sensibility admits of the introduction of a "swamping resistance" of 81 ohms, when used as a millivoltmeter for measuring a drop of ·01 volt on a current-carrying shunt, so that the temperature coefficient of the instrument as a millivoltmeter is less than ·04 per cent. per degree Centigrade.

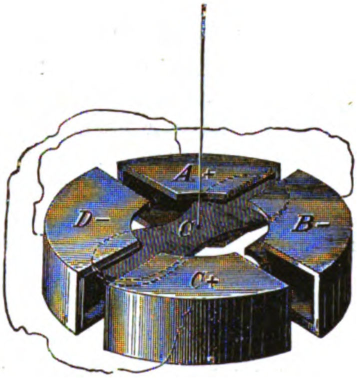


FIG. 189.—THE QUADRANTS IN LORD KELVIN'S ELECTROMETER.

For measurement of pressures, with external series resistances, a coil is wound with 100 turns, and has a total resistance, with the two suspension wires, of about 38 ohms, and a sensitiveness of 500 millimetres per micro-ampere at one metre. The damping of both coils is so arranged to give a slight overswing, which is found preferable to absolute aperiodicity, and the constancy of the zero is such that the instrument may be fully deflected for many hours, or even days, without causing a zero creep of 1 part in 2,000.

ELECTROMETERS.

The quadrant electrometer is an instrument that is indispensable for all galvanometric measurements of alternating quantities and also for delicate measurement of static potential differences; for this instrument we are indebted to Lord Kelvin. It consists essentially of four flat boxes of quadrant form, as shown in Fig. 189, and a peculiarly shaped "needle," the shape of which is also shown in Fig 189. The four boxes are placed close to one another, but not quite touching, so as to form a sort of circular box within which the needle is suspended. Opposite quadrants are connected together in pairs, one pair being connected to the positive pole of the potential difference to be measured, the other to the negative pole. The needle is either connected to one of these, or to an independent source of electrification. The needle is hence subject to forces tending to move it so as to become enclosed within the pair of opposite polarity, and so as to be removed from the pair of similar polarity. These deflecting forces are balanced by the suspension, which is usually of the bifilar type, and the needle is provided with a mirror, which is used in the ordinary way.

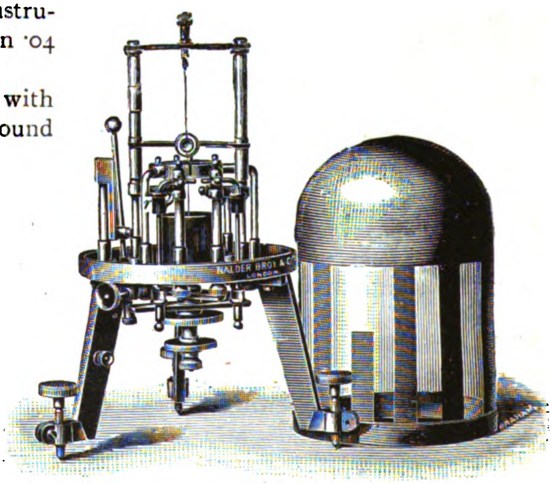


FIG. 190.—AYRTON, PERRY AND SUMPNER'S ELECTROMETER.

CHAPTER III.—CONTINUOUS CURRENT COMMERCIAL MEASURING INSTRUMENTS.

CLASSIFICATION—MOVING IRON TYPE—MOVING COIL TYPE—WATTMETERS—DEFLECTION WATTMETERS—HOT WIRE INSTRUMENTS—CARDEW—AYRTON AND PERRY—JOHNSON AND PHILLIPS—GEIPEL AND LANGE—HOLDEN—ELECTROSTATIC TYPE—SINGLE VANE—AYRTON AND MATHER—KELVIN MULTICELLULAR.

MEASURING instruments for use on continuous current circuits, whether they be voltmeters, ammeters, or wattmeters, all come under one or other of the following four broad classes :—

(1) "Moving iron" instruments,
(2) "Moving coil" instruments,
(3) Hot wire instruments,
(4) Electrostatic instruments.

Instruments of the first two types are electromagnetic, that is to say, they depend for their action on the mutual attraction or repulsion between a coil carrying a current and an adjacent magnetic field produced either by a permanent magnet, by the coil itself, or by another. In the first type, the current-carrying winding is stationary, the only moving portion being a small piece of iron which is acted upon by the field due to the current in the coil. On account of the simplicity of the moving part, one is enabled to make it of sound mechanical construction, which is a great advantage.

In the second type, a fine wire coil carrying a current proportional to the current or voltage to be measured is pivoted in such a manner as to be free to move in a powerful magnetic field, and communicates its motion to a pointer. This, of course, involves the conduction of current into and out of a moving coil, and complicates the construction considerably. A point in favour of the moving coil instrument, however, is the comparative ease with which an evenly divided scale is obtained. The coil moves, generally speaking, in a gap in a magnetic circuit, traversed by a powerful and uniform magnetic field. This renders it possible to obtain a very evenly divided scale.

MOVING IRON INSTRUMENTS.

Many of these instruments depend for their action on the tendency of any piece of free iron in a magnetic field to move in such a way as to reduce the reluctance of the magnetic circuit. Others depend on the mutual repulsion of similarly magnetised pieces of iron. An early variety of moving iron instrument, invented by Messrs. Ayrton and Perry, had a permanent magnet, the direction of whose field was at right angles to that of a winding carrying the current to be measured. The direction of the resultant field varied with the strength of the current, producing corresponding variation in the position of a pivoted iron needle. A beautifully even scale was obtained by carefully shaping the pole pieces. This type has, however, fallen into disuse owing to the expense of adjustment and calibration. One of the simplest forms is that depending on the action of a coil and plunger (Fig. 191). It consists of a solenoid, with a winding of high resistance for a voltmeter, and of low resistance for an ammeter. Above this solenoid, the axis of which is vertical, hangs an iron wire, with one end in the mouth of the solenoid, the top end being attached to a short lever or crank which projects from a horizontal pivoted spindle, to which is attached the pointer. Instruments of this simple type, with modifications, are still very largely used, chiefly on switchboards and for recording apparatus. The difficulty which had to be overcome with this, as with other forms of moving iron instruments, was the tendency of the scale to close up on the small readings. In the solenoid variety this is due to the fact that, as the iron wire enters the mouth of the solenoid, the pull per ampere and, consequently, the size of a scale division representing one ampere, increases very rapidly. In instruments of the recording variety, where it is essential to have an equally divided scale, a most ingenious device is made use of by some makers to obtain it. The section of the plunger is gradually decreased, being made large at the lower end and small at the upper, so that although the reluctance of the magnetic circuit is decreased by the reduced length of air path for the flux, it is also increased by the saturation resulting on the decreased section of plunger, and the two effects are made to balance. Thus the flux through the circuit is kept from increasing too rapidly, and an equally divided scale results. Of course, for the ordinary types of switchboard instrument, where an absolutely even scale is not required, the above complication is not necessary.

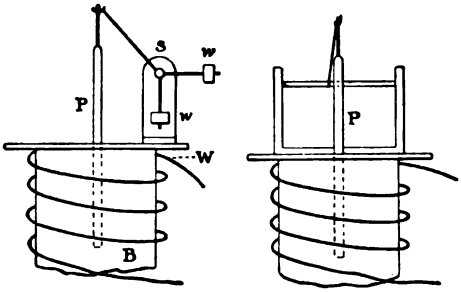


FIG. 191.—DIAGRAM OF COIL AND PLUNGER MOVEMENT. P, PLUNGER; B, BOBBIN; W, WINDING; *w*, *w*, BALANCE WEIGHTS; S, SPINDLE.

Fig. 192 shows a modern form of instrument, made by The Union Electric Co., which has a range from 0 to 400 amperes. It is exceedingly simple, the plunger being hung in the mouth of the solenoid by a spiral spring, and being attached to a finger which moves up and down the vertical scale.

A simple form of the repulsion type is shown in Fig. 193. The coil carrying the current is marked E. Inside this coil is a soft iron rod A; B is a curved piece of thin sheet iron, which is mounted on the lower end of the pointer D, and pivoted eccentrically to the bobbin at C. When current passes around the coil, both A and B are similarly magnetised, and consequently B is repelled and the pointer D moves over the scale.

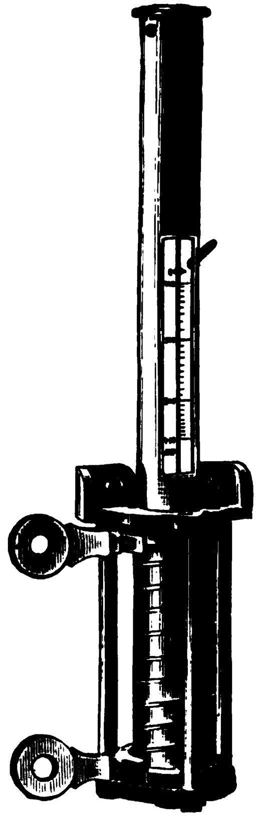


FIG. 192.—MOVING IRON INSTRUMENT.

The difficulty with regard to the uneven division of the scale is also met with in repulsion instruments, and an ingenious device is used by many makers to overcome this. Fig. 194 illustrates an instrument in which this is employed. The fixed portion consists of a bobbin, on which is wound the exciting coil, which carries the current to be measured. For an ammeter it is, of course, a few turns of large section, and for a voltmeter many turns of small section. Around, and covering part of, the inside circumference of this bobbin, is placed a thin strip or liner of iron, one end of which is bent up at right angles so that it projects into the space inside the bobbin. The moving portion is a light pair of arms of thin sheet metal, one of which carries a small piece of soft iron, the other a piece of zinc of equal weight to balance it. This vane is fixed on a steel spindle and mounted between jewelled centres.

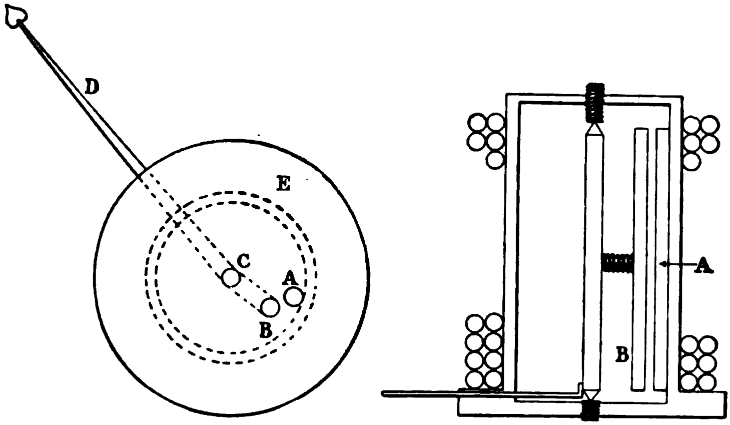


FIG. 193.—DIAGRAM OF REPULSION TYPE OF MOVEMENT. A, FIXED REPELLING IRON ROD; B, MOVABLE REPELLED ROD.

When the instrument is assembled, the moving portion is placed inside the bobbin, the piece of iron attached to one arm coming near the projecting piece of the liner, and, on the exciting coil being energised, these pieces of iron become similarly magnetised and repel one another. This ensures that the instrument will have a large starting torque, and not stick. As the current through the coil increases, the iron on the moving arm continues to be repelled by the iron liner, and, as the magnetism of *both* increases with the increasing current, the size of a scale division would increase largely were it not for the fact that the iron of the liner is shaped away, and so the field in it decreased, thus decreasing the repulsion of the moving iron on the arm. By suitably

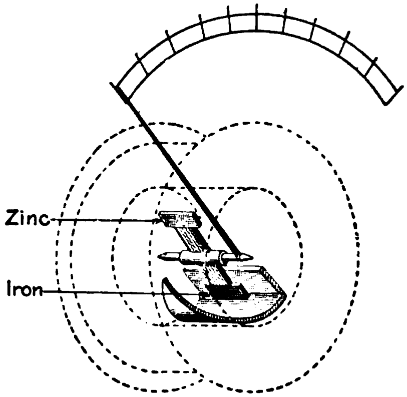


FIG. 194.—DIAGRAM OF REPULSION TYPE MOVEMENT WITH IRON LINER.

shaping away this liner it is possible to obtain a scale which is practically uniform, or, if so desired, the division may be made smaller in the middle and larger at the ends, or *vice versâ*. By adjusting the distances of the three small weights from the spindle, they may be made to balance the pointer in any position, and the instrument will therefore read the same in whatever position it may be. The damping vane renders it practically dead beat, and the zero may be adjusted by means of the hair spring.

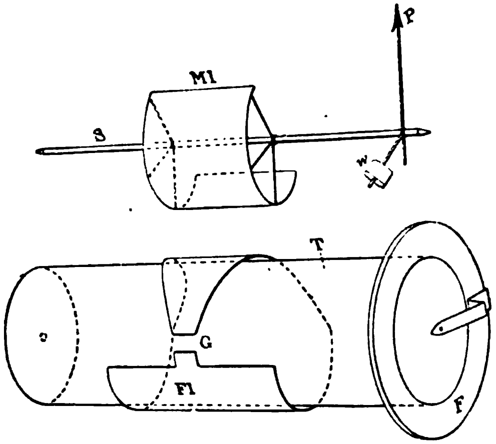


FIG. 195.—REPULSION TYPE MOVEMENT WITH IRON SLEEVE. T, BRASS TUBE; F I, FIXED IRON SLEEVE; G, AIR GAP; M I, MOVING IRON.

The exact structure of the fixed and moving parts varies considerably with different makers. Fig. 195 shows the construction adopted by Messrs. Evershed and Vignoles. The liner is made of thin sheet iron, shaped away as shown, and having no projecting piece. The moving iron, instead of being very small and carried at the end of an arm, is part of the surface of a cylinder, and is also of thin sheet. In the zero position, the top edge of the moving plate is just above the gap at H A in the external sleeve. When current

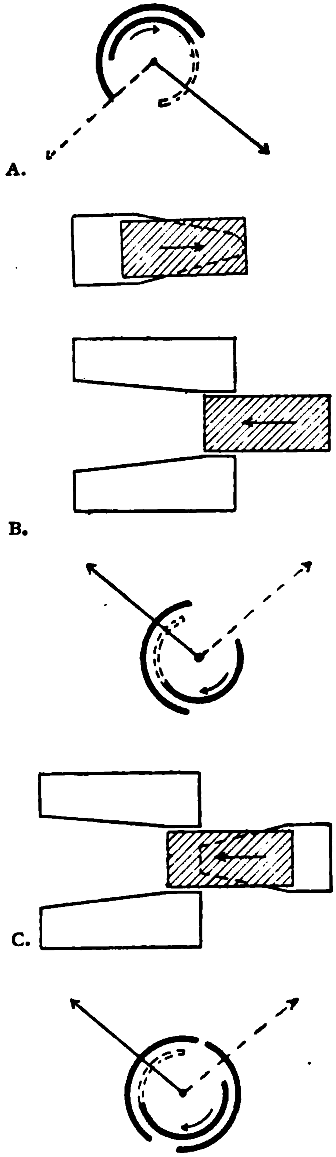


FIG. 196.—DIAGRAMS ILLUSTRATING MOVING IRON PRINCIPLES EMPLOYED BY UNION ELECTRIC COMPANY.

A, REPULSION TYPE; B, ATTRACTION TYPE; C, COMBINED ATTRACTION AND REPULSION. SHADED PORTION INDICATES MOVING IRON FLATTENED OUT, AND ARROWS INDICATE DIRECTION OF FORCE. UNSHADED PORTIONS, THE FIXED IRON SLEEVES REMOVED FROM BOBBIN AND FLATTENED OUT.

flows, both iron sheets are magnetised similarly, and therefore the moving iron, N, is repelled from the position where the field from the sleeve is strong into a position where the field is weak, that is to say, where the section of the sleeve is smallest. As in the instrument first described, by suitably shaping the sleeve, almost any desired scale can be obtained.

The errors to which moving iron instruments are liable are due to the following causes :—

(1) External magnetic fields,
(2) Change of temperature, in the case of voltmeters,
(3) The hysteresis error,
(4) Effect of temperature on the controlling spring.

The first can be guarded against by surrounding the working parts of the instrument by an iron screen, or putting it in an iron case. This is often done.

The second source of error is due to the fact that, as the coils of the voltmeter heat up their resistance increases, and, therefore, the current through them diminishes. This could be overcome by making the coils of some alloy, such as manganin or constantan, which has a negligible temperature coefficient. This, however, makes a coil of few turns and high resistance, which has the disadvantages that it provides few ampere-turns and may have too small a radiating surface to properly get rid of the heat generated. It is therefore customary to wind the coils with copper wire, making them of low resistance, and to put in series with them a large resistance of manganin or constantan. Thus the change of resistance of the copper coil is so small as compared with the total resistance that it is negligible.

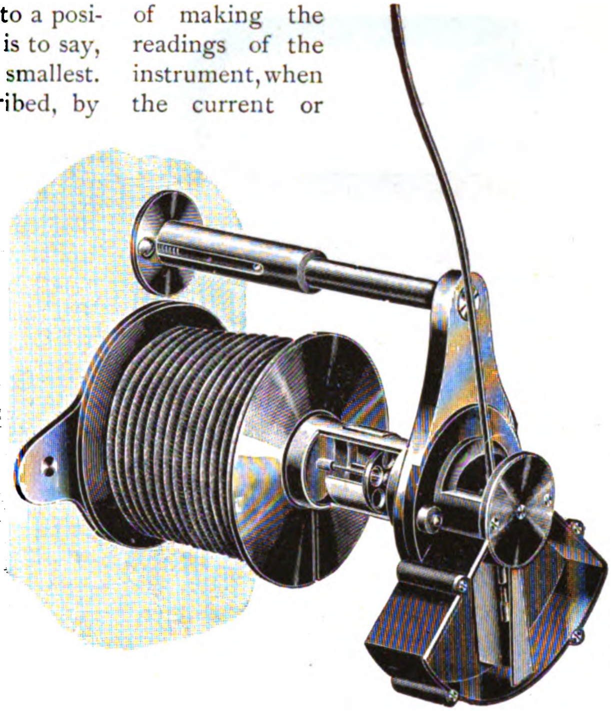


FIG. 197.—UNION ELECTRIC COMPANY'S MOVING IRON INSTRUMENT, REPULSION TYPE, WITH MOVEMENT DRAWN FORWARD SO AS TO EXPOSE WORKING PARTS. COVER OF DAMPING BOX IN FRONT REMOVED TO EXPOSE VANE.

The third cause of error has the effect of making the readings of the instrument, when the current or voltage is gradually decreased, higher than those obtained in ascending the scale. This is due to the residual magnetism of the iron parts that obtained at the high readings in ascending increasing the deflection at the smaller readings in descending. This is obviated by using only very soft iron, and keeping the iron parts as small as possible.

The fourth error, due to the expansion or contraction of the controlling spring with changes of temperature, causes a zero error. This can be obviated by using two controlling springs, one wound clockwise, the other counter clockwise, so that the effects of the two springs oppose one another.

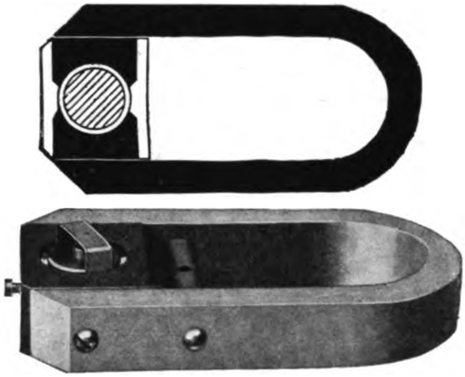


FIG. 198.—MAGNET, POLE PIECES, AND IRON CORE OF MOVING COIL INSTRUMENT.

MOVING COIL INSTRUMENTS.

In this type of instrument the moving portion consists of a coil of fine wire wound on a light frame or "former," usually of metal, placed in the field of a powerful permanent magnet, or, in some cases, in that due to another coil. Moving coil instruments are made by most of the leading firms of instrument makers, and the different varieties only differ in details. It will, therefore, only be necessary to describe in detail one make, and then point out the modifications to be found in other patterns.

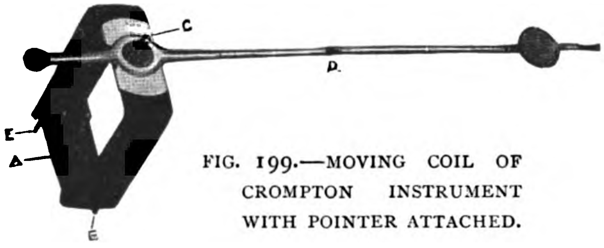


FIG. 199.—MOVING COIL OF CROMPTON INSTRUMENT WITH POINTER ATTACHED.

The instruments made by Messrs. Crompton and Co. form a very good example of what can be done in the way of standardisation and simplification, and we shall, therefore, describe one of these instruments at some length. Fig. 198 shows the permanent magnet, which is of the horse-shoe type, fitted with two mild steel pole pieces, which are built up in a solid block, with brass end plates (shown unshaded), and machined before being placed between the poles. Now it is essential, in order to obtain an evenly divided scale, that the field should be uniform over the range of movement of the coil, and also, to obtain large moving forces, that the field should be as strong as possible. Both these desiderata are obtained by the insertion of a mild steel cylinder (shown shaded in Fig. 198) in the space between the pole pieces. Between this cylinder and the pole pieces is left an annular gap, and it is in this gap that the coil moves. The insertion of the steel cylinder reduces the reluctance of the magnetic circuit, and, therefore, concentrates the field strongly, while the fact that the gap

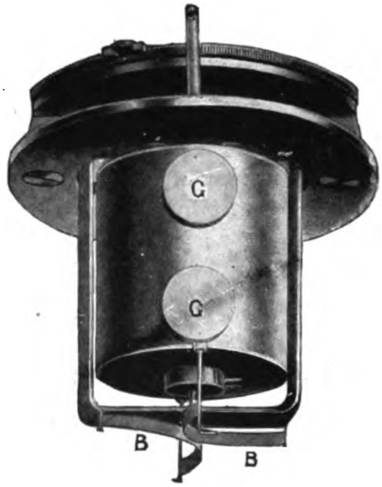


FIG. 200.—COMPLETE MOVEMENT OF CROMPTON MOVING COIL INSTRUMENT.

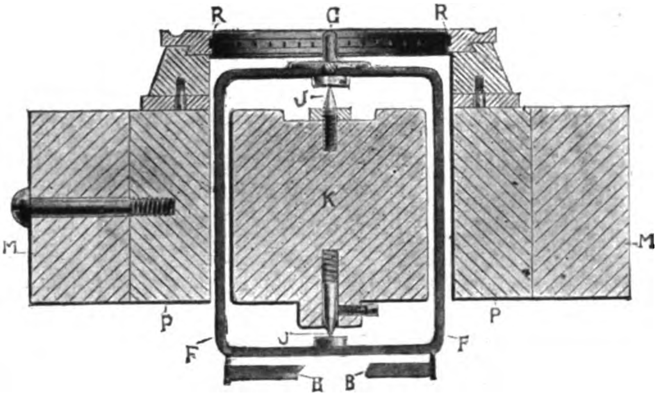


FIG. 201.—SECTION OF CROMPTON MOVING COIL.

is uniform insures a practically uniform distribution of the field. Fig. 198 also shows the coil in place in the annular gap. This coil is wound on a thin former of copper, and it is this former which renders the instrument "dead beat," that is to say, which brings it to rest without undue oscillation. When the instrument is put in circuit, or when the value of the current through it is changed, the pointer tends to oscillate about its new position. In doing this, the copper former cuts across the magnetic field, and eddy currents are thereby induced in it, which oppose its motion and speedily bring it to rest. By suitably proportioning the parts, an instrument can be made which will give its final indication without any oscillation at all. Fig. 199 shows the wound coil with pointer attached. A is one of the centres upon which the coil is pivoted; C is the pillar to which is attached the controlling spring; D is a small spiral spring, which can be moved along the pointer to accurately adjust the balance; and E E are the ends of the wire winding. Of course, the difficulty with moving coil instruments is to get the current into the moving coil, because if the connections employed are not perfectly elastic, errors are at once introduced into the readings. In this instrument the difficulty is got over by using, as connectors, two very thin strips of gold, which are so flexible that practically no error is introduced by their use. These strips are soldered at one end to the wires of the coil, and at the other to two insulated pins projecting from the steel cylinder. These, and the method of mounting the coil, are clearly shown in Fig. 200, from which it is evident that the complete movement, including coil, connections, controlling spring, and steel cylinder, can be removed in one piece. The parts G G are brass studs which ensure the movement being placed centrally in the pole pieces. Fig 201 shows a section of the working portion in position.

B B are the gold conducting ligaments.

C is the pillar to which the controlling spring is attached.

F F is the moving coil.

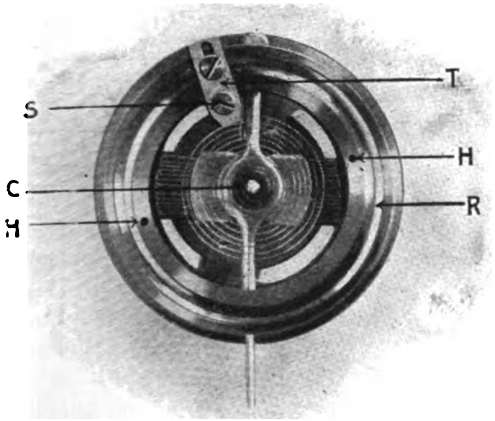


FIG. 202.—FRONT VIEW OF CROMPTON MOVING COIL INSTRUMENT.

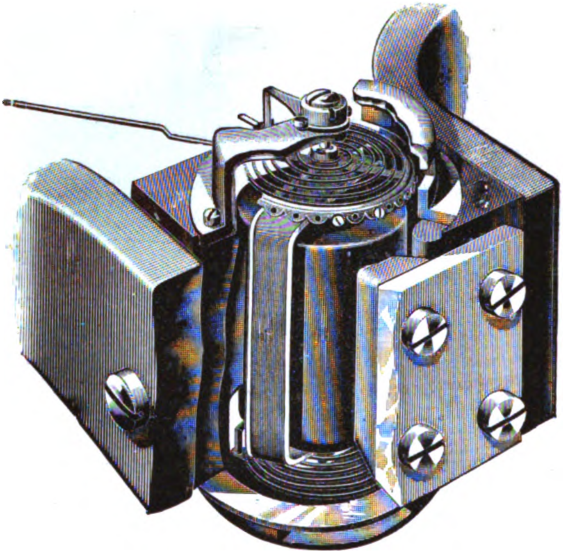


FIG. 203.—DETAILS OF WESTON'S MOVING COIL VOLTMETER.

K is the core.

J J are the pivots upon which the coil swings.

M M are the poles of the permanent magnet.

P P are the mild steel pole pieces.

R R is a movable ring to which the controlling spring is attached.

The lower pivot, upon loosening the set screw, is pushed forward by a small spiral spring, thus enabling the coil to be easily removed, and, when replaced, ensures that the pressure on the pivots shall be just the right amount. All parts are made to gauge, and are thus mechanically interchangeable. Moving coils having the same windings are interchangeable, subject to an adjustment of the controlling springs. Fig. 202 shows the means by which adjustment is effected. To adjust the zero, all that is necessary is to turn the milled ring, R, to which is attached one end of the controlling spring. To alter the strength of the controlling spring, the screw, S, is slackened, releasing the spring at T. This is then drawn through the slot, and clamped in the required position by tightening up the screw, S. An adjustment of this sort usually alters the zero, which can, however, be corrected by turning the ring, R, as shown above.

Fig. 203 illustrates the instrument made by the Weston Electrical Instrument Co., and Fig. 204 that made by Messrs. Evershed and Vignoles, and it will be seen that the difference in construction from the type above described is but slight.

The errors to which moving coil instruments are subject are as follows:—

(1) Variation in strength of the permanent magnet used,

(2) Temperature error,

(3) Temperature error of controlling spring.

The first error was at first a very serious one, but now magnets of almost constant strength can be produced very easily. This is done by artificially "ageing"

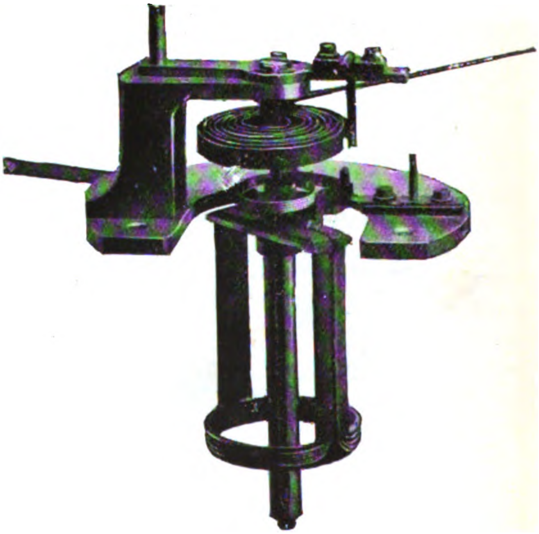


FIG. 204.—MOVING COIL OF EVERSHED INSTRUMENT AND ITS MOUNTINGS.

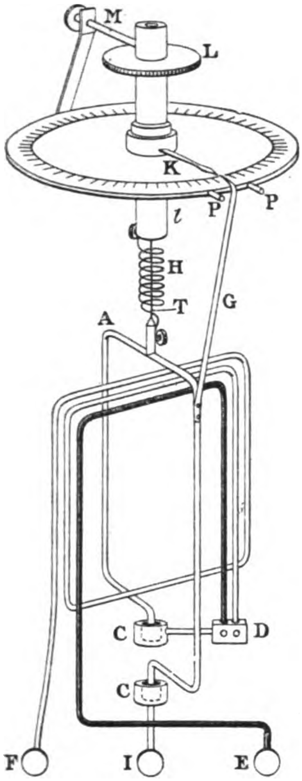


FIG. 205.—CIRCUITS AND ARRANGEMENT OF SIEMENS' DYNAMOMETER.

them. After the steel has been magnetised by being placed in a coil carrying current, it is left for some time, and then subjected to a demagnetising action, being tapped the while with a wooden mallet. This causes it to lose a certain portion of its magnetism. It is again allowed to rest for a time, and slowly regains a small part of the lost magnetism. After this it is practically permanent, and, unless subjected to very rough usage or to powerful external magnetic influences, will not vary perceptibly.

The second source of error is obviated in exactly the same manner as that described on page 263, when referring to "moving iron" instruments. In "moving coil" instruments it is exceedingly important to get as many ampere turns on the moving coil as possible, and this precludes all possibility of using coils of any other material than copper. The series resistance is so large that it entirely swamps the change of resistance of the copper coil.

How the error due to the change of temperature of the controlling spring is overcome has already been explained on page 263.

WATTMETERS.

Under the class of "moving coil" instruments come wattmeters for use on continuous current circuits. These depend for their action on the mutual action of two coils, one of which carries the main current, the other a current proportional to the voltage of the circuit. One of the earliest and best known of these instruments is the Siemens' dynamometer, which can also be adapted to measure both voltage and current. Fig. 205 shows its

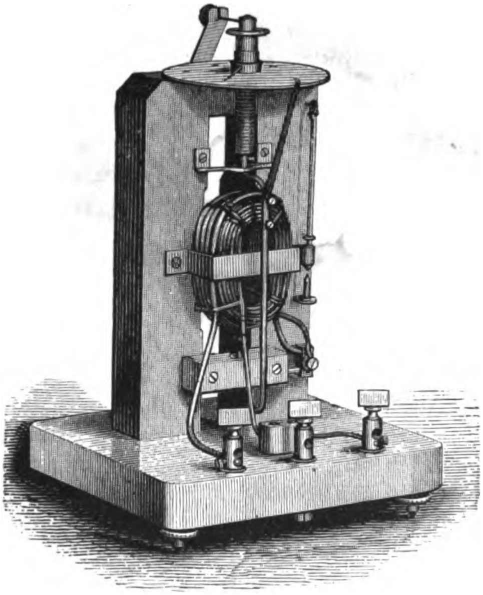


FIG. 206.—GENERAL VIEW OF SIEMENS' DYNAMOMETER.

arrangement diagrammatically, and Fig. 206 is a photograph of the actual instrument. The thick wire coil, which carries the main current, is shown at A, and is suspended by means of the silk thread, T, from the spindle, M, by rotating which the thread can be coiled up and the coil lifted and allowed to swing free. Attached to the moving coil is a long helical spring of phosphor-bronze, the upper end of which is fixed to the milled headed washer, L, which carries a pointer, K. The thick wire coil also carries a pointer, G, the end of which is bent over and moves along the scale, J, between the two stops, P P. The ends of the coil dip into two mercury cups directly below the point of suspension. The fine wire coil, B, is fixed by means of clips (which for alternating current instruments should be non-metallic) to the vertical supports. In many instruments two fine wire fixed windings are provided, thus increasing the range and sensibility obtainable. The instrument is used as follows: It is first levelled by means of the screws provided, and the moving coil adjusted so that it swings freely. Current is then passed through the moving coil only, and the instrument turned about until the pointer is midway between stops, P P, and points to zero, the pointer, K, also being at zero. This is done to ensure that the field due to the current in the moving coil shall be the same in sense and direction as that due to the earth, thus putting the coil in its position of rest in the earth's field, and rendering the instrument independent of it.

After this has been done, the current in the circuit whose power is to be measured is sent round the moving coil, care being taken to send it in the same direction around the coil as in the first instance. In fact, the connection to one mercury cup should not be undone. The fixed, fine wire coil is now connected across the circuit, the current flowing through it then being proportional to the voltage of supply. When this is done, owing to the mutual attraction or repulsion between the two coils, the pointer G, moves over against one of the stops, P. The fine wire coil should be so connected that the pointer moves in a counter clockwise direction. The milled head, L, is now turned in a clockwise direction, until the torque exerted upon the coil by the spring, H, just balances the magnetic torque, and the pointer, G, is again at zero. The angle through which it has been necessary to turn the pointer, K, then forms a measure of the torque exerted. Let D be the angle through which the pointer has to be turned; c_1, the main current; c_2, the current in the fine wire coil; V, the voltage. Then

$$D \propto c_1 \times c_2$$

but $$c_2 \propto V$$

$$\therefore\ D \propto c_1 \times V$$

but $$c_1 V = \text{the power in watts} = W$$

$$\therefore\ D \propto W$$

$$\therefore\ D = K W.$$

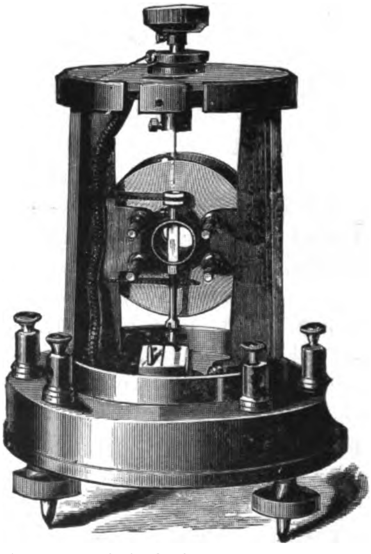


FIG. 207.—INTERIOR OF SWINBURNE'S WATTMETER.

K is called "the constant" of the instrument.

When current is to be measured, both fixed and moving coils are made of thick wire and joined in series, the current being proportional to the square root of the deflection; and, of course, when voltage is to be measured, the coils are both of fine wire, the voltage also being proportional to the square root of the deflection.

The instrument has the advantage that it can be used as an ammeter or a voltmeter for both alternating and continuous currents, and, owing to the absence of iron, it is not affected by frequency or wave form. It can also be calibrated with continuous current for use on an alternating current circuit. As a wattmeter, however, certain modifications are necessary to fit it for use on an alternating current circuit, for which see page 283. It possesses the disadvantages of not being portable—on account of the mercury cups—not being direct reading, and is affected by external fields. In practice, the constant, K, is not truly constant, owing to irregularities in the spring, and for accurate work a calibration curve should be employed. Wattmeters like the above, which have to be adjusted until no deflection is obtained, are known as the "zero deflection" type, in distinction to those in which a pointer moves over a scale and gives a direct reading.

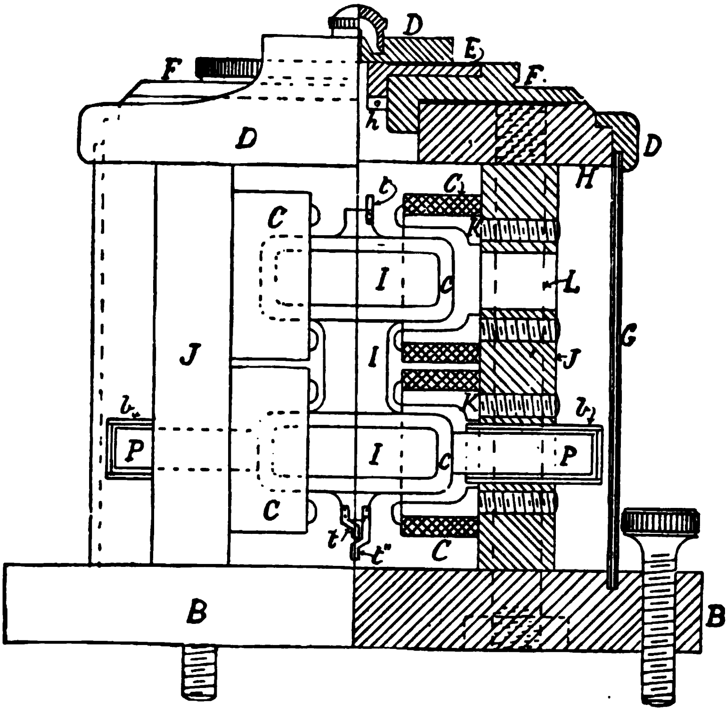


FIG. 208.—THE DUDDELL-MATHER STANDARD WATTMETER (HALF SECTIONAL ELEVATION).

Another well-known type of "zero deflection" wattmeter is that due to Swinburne, and illustrated in Fig. 207. There are two thick wire stationary coils, through which the main current passes. The movable coil is small, and consists of fine wire wound on a cylindrical piece of mica, through which passes an ivory spindle. This spindle serves as a guide, entering holes in the interior tube of the fixed coils. To the top and bottom of the ivory spindle are fastened phosphor-bronze strips, which convey the current to and from the coil. The lower strip is fixed, but the upper is attached to a milled torsion head with a pointer, as in the Siemens dynamometer. In series with the moving coil is connected a fairly large resistance (for alternating current work it must be non-inductive, for reasons to be explained later), which reduces the temperature error, as before explained.

Another, and newer, example of the same type is that due to Messrs. Duddell and Mather, and is shown in Fig. 208. The moving coils, *c c*, of which there are two, are of fine wire, and are mounted in the same plane, being so connected that the current circulates round them in reverse directions, making the moving system independent of stray magnetic fields. Connection is made to the coils by means of mercury cups in the line of the suspension. The magnetic torque is counteracted by a spiral spring connected to a milled torsion head as in the other instruments. To the moving coils are attached vanes, P P, projecting into glass boxes, upon the fronts of which are engraved short scales. These vanes serve the double purpose of damping the motion of the coils and of indicating when they are in the zero position. There are two sets of fixed coils at right angles to the moving ones. These fixed coils are wound in sections, of heavy wire, and all the ends are brought out to a convenient plug-board, by which they can be connected either in parallel or in series, thus giving a large range of sensitiveness. Great care has been taken in the construction of the instrument to avoid the use of metal as far as possible, and the scale of the instrument is calibrated to read directly in watts, or only to need multiplying by a simple factor when other combinations of the coils are used.

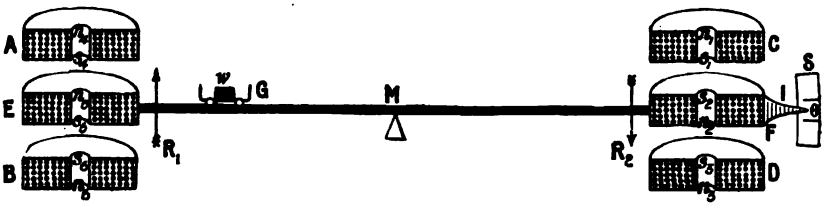


FIG. 209.—DIAGRAM OF CIRCUITS AND ARRANGEMENT OF KELVIN BALANCE.

Another type of instrument which can be adapted to measure either current or watts is the Kelvin balance. This is depicted diagrammatically in Fig. 209. A long arm is balanced on a knife edge at M, and carries at each end a coil, E F, of thick or thin wire, depending on whether the instrument has to measure current or watts. Above and below the coils E and F are other fixed coils, A, B, C, D, of thick wire. These are so connected that the coil E is repelled by B and attracted by A, and the coil F is repelled by C and attracted by D. Thus the whole system tends to rotate in a clockwise direction about M. This tendency is counteracted by moving a small weight, W, on a carriage, G, along the beam. A scale, S, is provided, over which moves a pointer attached to one end of the balance arm, showing when the scale arm is in exact equilibrium. A scale is engraved on the arm, which enables the distance of the weight, W, from the knife edge, M, to be read. This distance is a measure of the torque exerted, the weight, W, being constant.

In a current balance the torque is proportional to the square of the current, but in a watt balance the watts are directly proportional to the torque, as in the case of the dynamometer. In the ampere balance, the great difficulty is to get the current into and out of the moving coils, as it cannot be sent through the knife edges on account of the heating and high contact resistance. It is done by using, as connectors, a number of fine copper threads, which form a fairly flexible connection. As the current to be measured increases, however, the number of ligaments becomes so large that the instrument for heavy currents has been modified, and the total current is only carried by the fixed coils, the moving coil carrying a small portion, the value of which is measured on another balance.

Fig. 210 is a photograph of a current balance with a range of from 1 to 100 amperes. The watt balance has been considerably modified from the above, but the principle upon which it works is, of course, identical. The moving coil is made the voltage or fine wire coil, and this obviates the difficulty of dealing with large currents experienced in the current balance.

DEFLECTION WATTMETERS.

In station and in practical work it would be exceedingly inconvenient if an instrument had to be used in which it was necessary to reduce the deflection to zero before a reading could be obtained. It is, therefore, almost a necessity, especially on circuits supplying a rapidly varying load, to have a direct-reading, dead-beat instrument. There are now a good many of these on the market, most of which are satisfactory, on continuous current circuits. One of the simplest of these is the Kelvin engine-room wattmeter. The working parts of this are shown in Fig. 211. The heavy current coil, in which there are two turns with their axes vertical, consists of an 8-shaped loop of copper rod, attached to massive terminals. The moving coils, wound astatically with fine wire on a light aluminium structure, are shown in

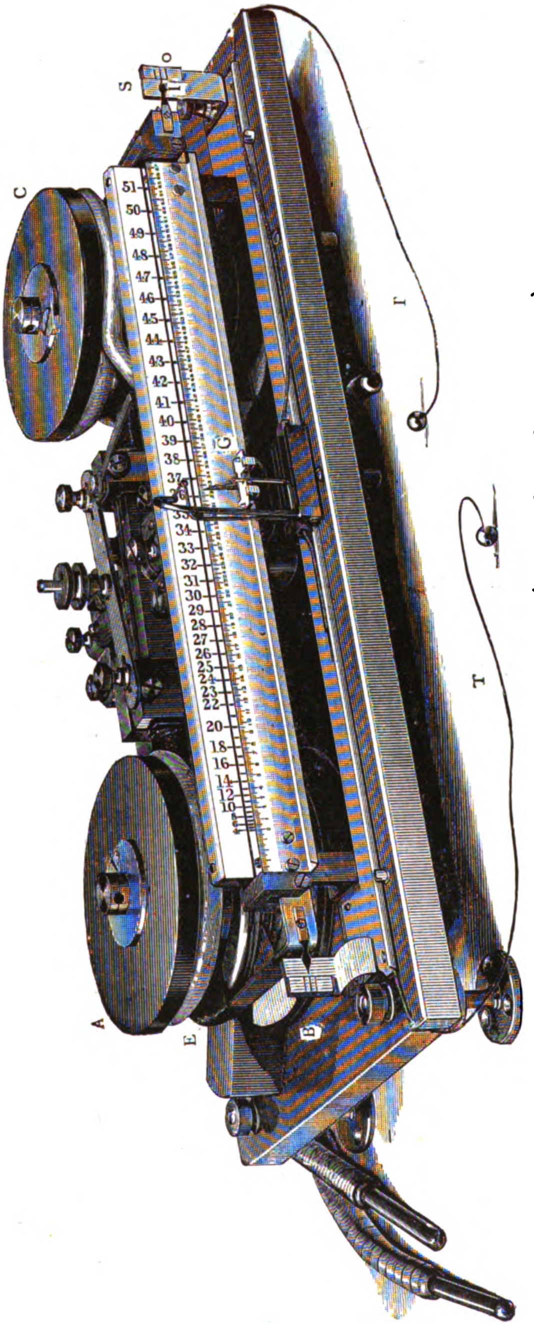


FIG. 210.—THE HEKTO-AMPERE BALANCE (RANGE 6 TO 600 AMPERES).

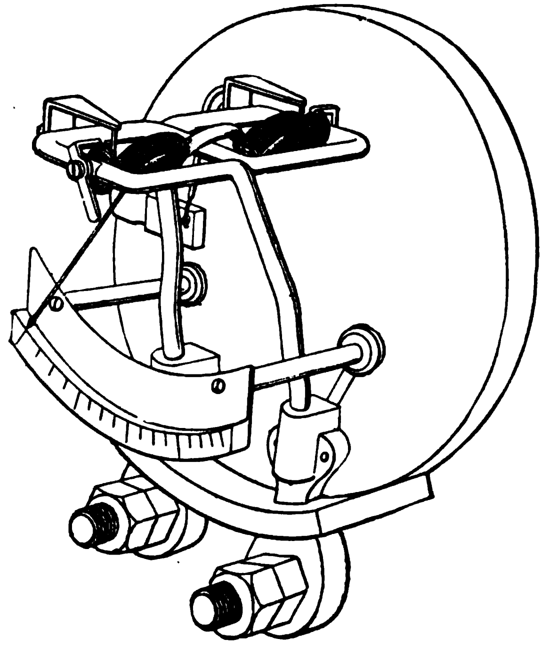


FIG. 211.—LORD KELVIN'S ENGINE-ROOM WATTMETER.

Fig. 212. These coils are mounted with their axes tilted slightly, upon hook supports, inside the heavy current coil. The movement is controlled, and the current conveyed into and out of the coils, by means of two hair springs of palladium strip. The resistance of the two fine wire coils is about 200 ohms, and as only 33 milliampères are required as a maximum, the coils are connected in series with a large non-inductive resistance with a negligible temperature coefficient. For pressures up to 600 volts this is contained in the base of the instrument, but for higher pressures it is external. The scale is a nearly uniform one, and is calibrated to read direct in watts or kilowatts.

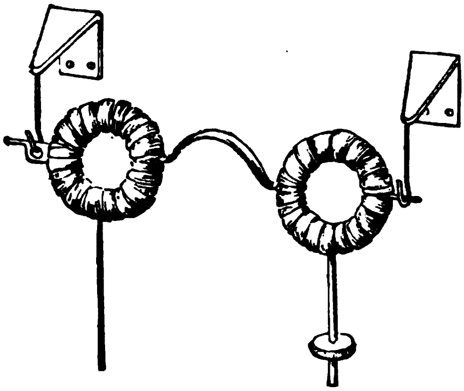


FIG. 212.—MOVING COILS OF THE KELVIN ENGINE-ROOM WATTMETER.

An ingenious wattmeter, also of the dynamometer type, is made by Messrs. Hartmann & Braun, and is shown in Fig. 213. The moving coil system consists of two fine wire coils, wound astatically and fixed on the opposite ends of an arm of sheet aluminium, which is mounted on a spindle. The axes of the coils are parallel to the spindle, which also carries a pointer E, two balance arms with weights, and a damping vane which moves in box, F. The controlling force is supplied by a hair spring, which also serves as one connection to the moving coil, the second connection being made by a very thin strip of absolutely pure silver, which is exceedingly soft and pliable. The fixed coil, C, which carries the main current, has its top tilted forward, and is so placed that the spectacle-shaped moving coil is just opposite to its mouth. Thus the whole fixed coil is leaning forward over the moving one. When the instrument is working the moving coil *b* has a field which is opposite in direction to that of C, while *a* has a field of the same direction as C. Consequently, coil *b* tends to move out of C to where the field of C is weakest, and coil *a* tends to move into C, to the strongest part of its field. The result is that the moving coil tends to rotate about halt a revolution, moving the pointer over the scale. In no part of the instrument is there any large mass of metal in the magnetic field.

An excellent form of wattmeter is made by the Weston Electrical Instrument Company, Fig 214 showing the principle upon which it works. In order to show the fine wire coils and the controlling springs, one of the fixed coils for carrying the main current has been removed. S is the moving coil, consisting of many turns of fine wire, and is mounted on aluminium pivots which work between jewelled centres. The movement is controlled by two hair springs which also serve as connectors. On each side of the moving coil is placed a current coil, M, the current coils being so connected that their fields are in the same direction. The moving coil tends to turn so that its field is also in the same direction as that due to the field coils, as in other forms of this type of instrument. The damping of the oscillations of the pointer is effected by two vanes, W W, which work in an enclosed metal case, C, the cover having been removed from the instrument in the illustration. The moving coil is connected as usual in series with a non-inductive resistance, made of a Weston patent alloy having a negligible temperature coefficient, the temperature error being thus reduced to a minimum. The weight of the moving parts of this instrument is only twenty grains, the coil, S, not being wound on a former. The direct current instrument made by the same firm has a moving coil wound on an aluminium former, the eddy currents in which serve to damp the oscillations of the pointer. The resistance material is made up of thin strips and is wound on thin sheets of mica, this construction having a very high insulation and large radiating surface and small capacity.

There are a great many other makes of direct-reading wattmeters, but they all (with the exception of those for exclusive use on alternating current circuits) depend on the dynamometer principle for their action, and only differ in its application.

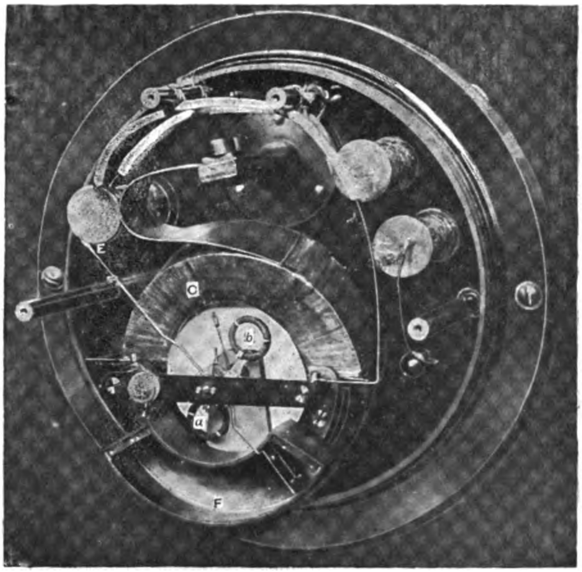


FIG. 213.—THE HARTMANN AND BRAUN WATTMETER.

HOT WIRE INSTRUMENTS.

In these instruments the heating effect of the current, combined with the expansion of a metallic wire when heated, is used as a measure of the magnitude of the current. It is a well-known fact that the elongation of a wire when heated is proportional to its rise in temperature. Also, the heat units developed are proportional to the square of the current.

Thus, if the rate of radiation of heat by the wire were constant, and if the wire had a constant resistance at all temperatures, the elongation of the wire would be proportional to the square of the current. However, owing to the fact that the wire is a fine one, and cools very rapidly, the elongation is found to be more nearly proportional to the first power of the current, especially on the higher portion of the scale when the wire is really warm. Hot wire instruments have the advantage that they will measure alternating or continuous currents with equal accuracy, and are unaffected by frequency or wave form. They are also dead beat, direct reading, are absolutely independent of external magnetic fields, and have no appreciable temperature error. Their chief disadvantage is that they consume rather more energy than either the "moving iron" or the "moving coil" types.

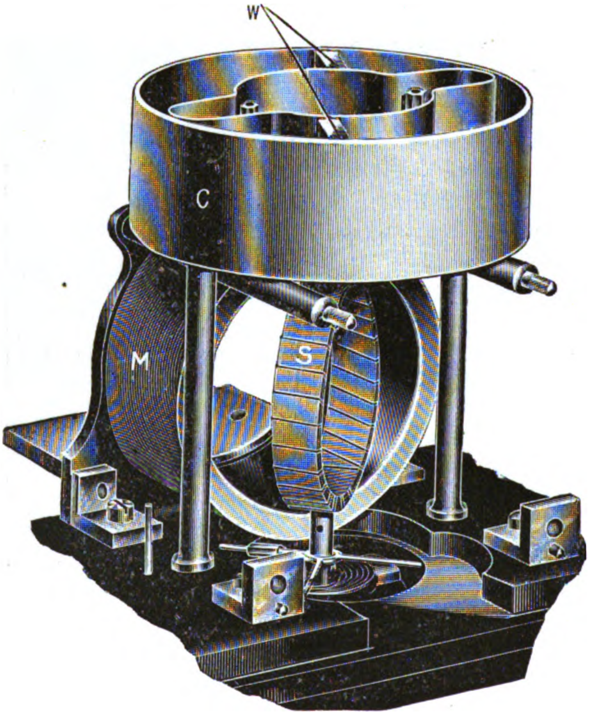


FIG. 214.—WESTON WATTMETER.

THE CARDEW INSTRUMENT.

The first type of hot-wire voltmeter to be commercially made was that due to Major Cardew. The internal construction of this instrument is shown diagrammatically in Fig. 215. The two ends of the wire are attached to two terminals, T T. From thence it passes under the pulleys, P_1 P_1, being kept in tension by the button, P_2, at the middle of its length. The button is carried on a block, to the upper part of which is attached another wire, C, carried round the pulley, P, and is kept in tension by the spring, which is capable of being adjusted by the screw, A. The pulley, P, is connected through a multiplying gear, shown in the diagram by a rack and pinion, to the pointer, N, One great disadvantage of the instrument is the length of the brass tube containing the hot wire, and although the instrument was at one time much in vogue, it does not now appear to be made in any great quantity; it has, further, the serious disadvantage of indicating unsteadily. This may be avoided by working it in a horizontal position, but there is then a loss of accuracy owing to greater friction. The consumption of the current is also high, being about 0·3 ampere at 100 volts.

THE AYRTON AND PERRY INSTRUMENT.

This is an instrument of a most ingenious kind, in which use is made of the tendency of a twisted strip of metal, to which a permanent set has been given, to untwist when heated. Although no use

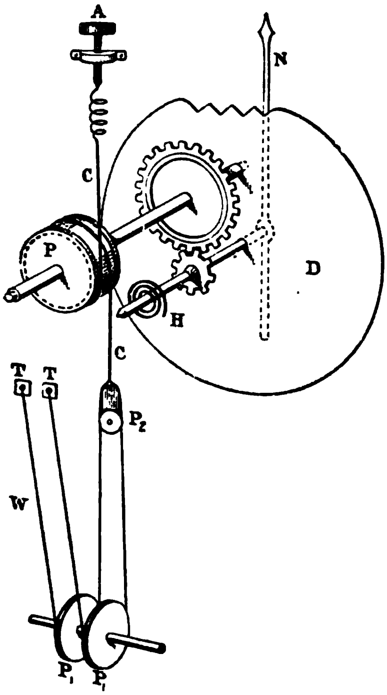


FIG. 215.—THE CARDEW INSTRUMENT.

is made of a hot wire, yet the description of this instrument is rightly included here, as it works on the expansion principle. In the manufacture of the instrument, the mechanism of which is shown in Fig. 216, a thin strip of metal, C, is taken and a pointer, P, attached to the middle. The middle of the strip is then twisted by carrying the pointer through two or three revolutions, and clamping it. Whilst in this position a current largely in excess of that which the strip will normally have to carry is passed momentarily through it. The clamps are then removed, when the strip partly untwists, but retains a considerable permanent twist. The strip is mounted so that a slight tension is constantly exerted upon it by means of a spring, S, and this causes the strip to untwist by a further small amount. If now any current be sent through the strip it expands, and in so doing untwists yet more, communicating a movement to the pointer. The instrument possesses the advantages of other hot wire instruments, with the exception of being free from temperature errors, but for some reason their manufacture appears to have been discontinued.

THE JOHNSON AND PHILLIPS INSTRUMENT.

One of the most generally used types of hot wire instrument is manufactured by Messrs. Johnson and Phillips. It is made in the circular dial form, and Fig. 217 shows the general arrangement of the working parts of an ammeter. The whole of the parts are mounted upon an expansion plate, made from a special alloy whose coefficient of expansion is the same as that of the hot wire, so that

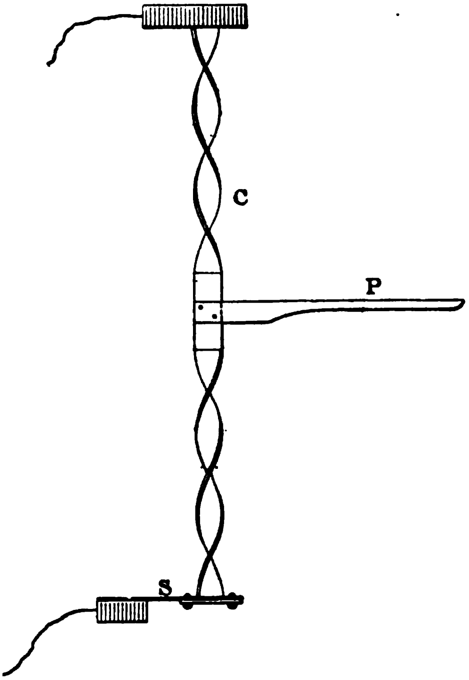


FIG. 216.—THE AYRTON AND PERRY INSTRUMENT.

any expansion or contraction of the wire due to variation in atmospheric temperature is corrected for.

The expanding wire, A B, is made of platinum silver, and is about 6¼ in. long. At one end it is attached to the fixed stud, B, and at the other to a device, A, for adjusting the tension. At C, near the middle of A B, is fixed one end of a phosphor-bronze wire, the other end of which terminates at the fixed stud, F. At E, near the centre of the wire, C F, is attached a fibre of cocoon silk, which passes around the grooved metal pulley at W, and is fastened to the spring, S, which permanently keeps the silk and both wires in tension. On the same spindle as the pulley, W, is placed the pointer, P, and the light aluminium disc, D, which moves between the poles of a powerful permanent magnet, and damps the movement of the pointer. The action of the instrument is at once obvious. When the wire, A B, expands under the heating influence of the current, the sag is immediately taken up by the wire, C F, whence the motion is transmitted to the spindle through the silk fibre. By this transmission through wire, silk, and pulley, the motion of the original wire is very largely magnified.

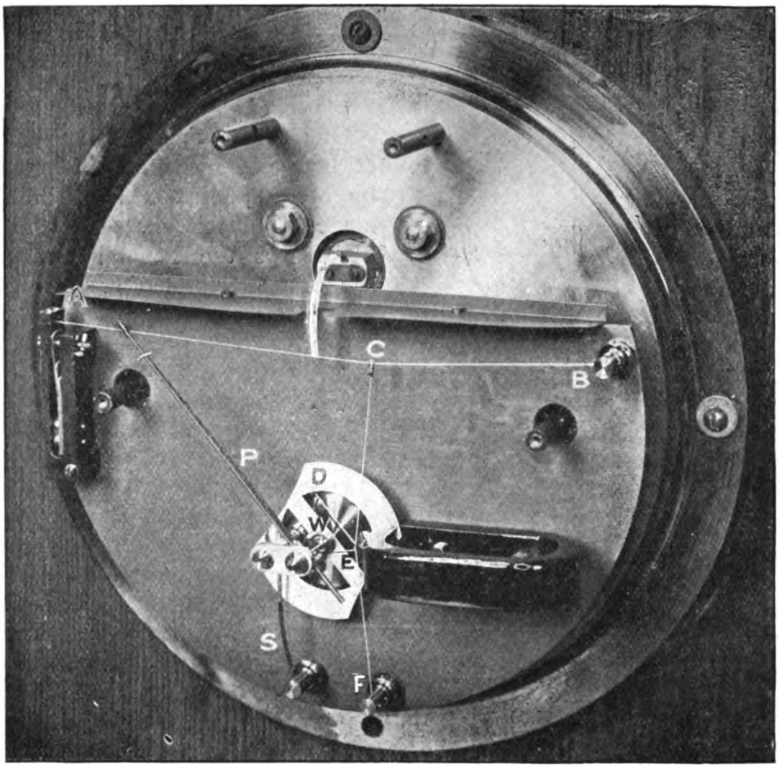


FIG. 217.—INTERIOR OF HOT WIRE AMMETER MADE BY MESSRS. JOHNSON AND PHILLIPS.

The main current, of course, passes through a shunt, the resistance of which is such that the potential difference across its terminals at full current is from 0·2 to 0·3 volt. The hot wire, which is considerably thicker than that used in the voltmeter, is divided into 2 or 4 equal parts by small tongues of silver foil. These are connected as shown in Fig. 217, so that the current flows through all the parts in parallel. A maximum current of from 4 to 5 amperes can thus be sent through the hot wire. The shunts for these ammeters are made of "constantan" resistance metal, and can be made of almost any capacity, with a drop of 0·2 to 0·3 volts over them. The lowest reading which can be obtained on these instruments is about one-tenth of the maximum reading, and they will stand double their maximum scale current for a short time without injury. The construction of the voltmeter is somewhat different from that of the ammeter, inasmuch as there is placed in series with the hot wire a non-inductive resistance made of a metal having a negligible temperature coefficient. Moreover, the whole of the current passing through the instrument traverses the hot wire. Both voltmeters and ammeters can be used either on continuous or alternating current circuits, and are unaffected by frequency or wave form. The scale obtained in these instruments is remarkably clear, and nearly uniform over the greater part of its range.

THE GEIPEL AND LANGE INSTRUMENT.

Another ingenious adaptation of the same effect is embodied in the instruments made by Messrs. Geipel and Lange, the working parts of which are shown in Fig. 219. The hot wire, K, is fixed at A to the upper bar, J, its lower end being joined to one end of a rocking bar, E, whose opposite end is in connection with the indicating needle through the thread, F, and a pulley on the axis of the needle. A tension is kept on the hot wire by the small spring, S, seen above the needle. When current passes through the wire, the latter expands, allowing the bar, E, to rock, and transmit its motion to the pointer by means of the thread, F, which passes once round the pulley on the needle spindle. The compensation for the external changes in temperature is effected in the following manner.

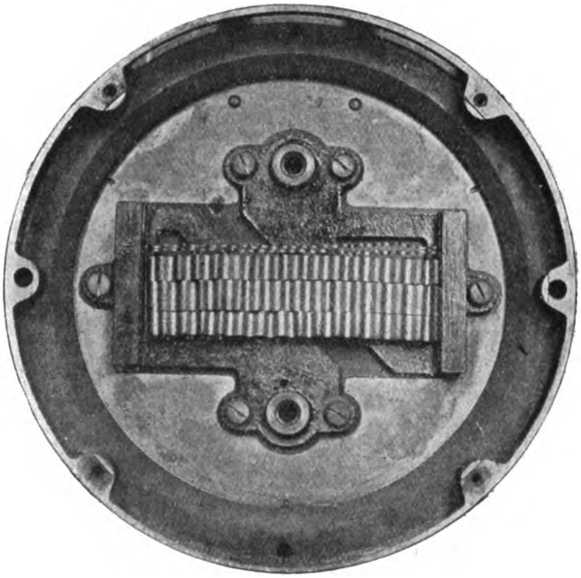


FIG. 218.—BACK VIEW OF HOT WIRE AMMETER SHOWING SHUNT.

A number of wires, B, of a material whose coefficient of expansion is the same as that of the hot wire, are fixed at their lower ends to the bottom bar, G, of the system, and attached to the top bar at their upper ends. This upper bar is pivoted at D, and tension is maintained in the wires, B, by an adjustable spring, C, pulling on the lower bar, G, through a rod, H. Thus when the hot wire changes its length owing to any *external* change of temperature, the wires, B, also change by the same amount, and allow that end of the bar, J, to be moved upward by the downward pull of the spring, C; there is then no appreciable movement of the lower end of the hot wire from this change, and consequently none of the lower rocking bar. If the compensation is to be perfect, the difference in the distances of the hot wire and the wires, B (if they are all of the same length), from the point, D, must be allowed for in selecting the material of which the wires, B, are made. Further, care would appear to be needed in shielding those wires from radiation of heat from the hot wire. The voltmeters are, of course, provided with a series resistance, and the ammeters with a shunt. The current used by the voltmeters for the maximum deflection is only ·1 amperes, and the drop across an ammeter and shunt is only ·15 volt, so these intruments are not very wasteful of power. Fig. 220 shows an ammeter connected to its shunt, which is suitable for 1,000 amperes. It will be noticed that in this type of instrument the scale is fairly even above half the maximum reading, and equal to many moving iron instrument scales below that.

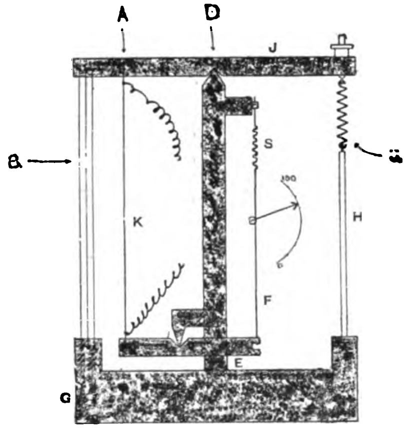


FIG. 219.—DIAGRAM OF MECHANISM OF MESSRS. GEIPEL AND LANGE'S HOT WIRE INSTRUMENT.

THE HOLDEN INSTRUMENT.

Another instrument in which the sag of a hot wire is made use of for indicating purposes is that devised by Major Holden for recording work. Fig. 221 illustrates a voltmeter, reading to 100 volts. The hot wire in this instrument is of considerable length, about eight feet, and has a resistance of nearly 1,000 ohms. It is passed around grooved cylinders which are made of an artificial stone having a very high insulation, the cylinders are mounted on spindles running in highly-polished sapphire bearings. The ends of the hot wire are fixed to the two terminals which are adjacent to the rollers, these can be plainly

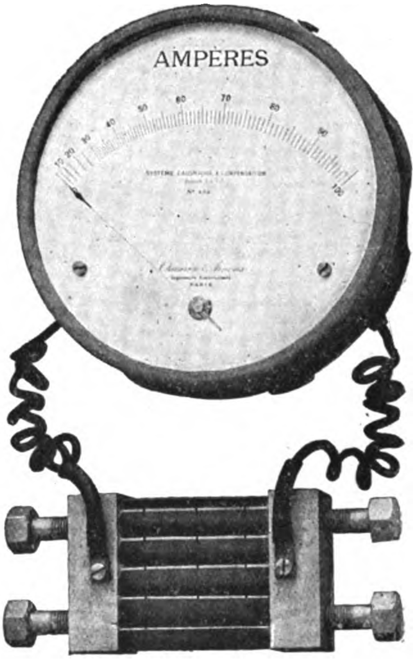


FIG. 220.—GENERAL VIEW OF MESSRS. GEIPEL AND LANGE'S AMMETER WITH SHUNT.

seen in the accompanying illustration. Upon the lower set of stretched wires thus formed rests another grooved cylinder, which is connected with the pointer, and is so balanced by means of counterweights that it always presses lightly on the hot wires. The end of the pointer is provided with a pen which moves over a chart fixed to a uniformly rotating drum. The pointer is so made as to be capable of swinging in two vertical planes at right angles to each other, its movement in one plane being determined by the sag of the hot wire and being used for the measurement. The other movement is allowed in order to reduce the friction between the pen and paper, the drum carrying the chart being so placed as to slightly tilt the pointer, and the pen is therefore pressed on the paper by gravity. The force to move the pointer is much greater in this instrument than in those using a singly stretched wire, owing to the number of turns used, and the amount of friction existing between pen and chart is relatively so small that errors due to it are eliminated from the record. In ammeters of this type the wires are put in parallel, and arranged to have a drop of about 0·3 volt over them at full current: they are, of course, used with a shunt. In the case of the voltmeters, however, no external resistance is necessary up to 300 volts, on account of the considerable length of wire which can be employed, the whole length being turned to useful account.

ELECTROSTATIC INSTRUMENTS.

Electrostatic instruments depend for their action on the mutual force between neighbouring electrified bodies; the principle is exclusively applied to voltmeters since a very considerable difference of potentials is required to produce sufficient forces for commercial instruments· indeed, voltmeters reading so low as 40 volts are scarcely more than laboratory instruments, and do not begin to be really satisfactory for ordinary use until about 100 volts are reached.

For such low values as these, a multicellular arrangement, described below, is desirable, but not absolutely necessary. The operation of these instruments is so simple that it will be readily understood in each case below where the construction is described. The one fact to be borne in mind is that the forces at work are always such as to tend to increase the capacity of the system (*see* Chap. V., Sec. V.) and that the magnitude of the force is great if the rate of change (with regard to space) of this capacity is great.

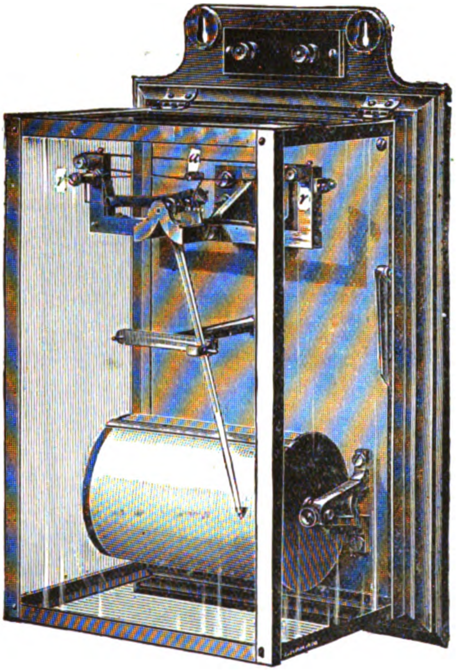


FIG. 221.—HOLDEN'S HOT WIRE RECORDING VOLTMETER.

SINGLE VANE TYPE.

The simplest form of electrostatic voltmeter is that used for the measurement of extra high pressures, say up to 30,000 volts. One of these instruments is illustrated in Fig. 222. The moving part consists of a single metal sheet, A, of the shape shown, to which is attached a pointer, P, and an arm carrying balance weights, B C, by which the calibration can be altered. The fixed part consists of two X-shaped pieces of metal placed near to one another to form a cell, into which the moving inductor, A, is free to travel. In the zero position the moving part is very nearly out of the cell formed by the fixed part. When the fixed and moving parts are oppositely electrified by being put into circuit, the latter is attracted into the former by an amount depending on the difference of potential between them. The control is a gravity one, and is furnished by the weights, B and C. The instrument is used in a vertical position, with a glass front, which is as a rule provided with an earthed strip of tinfoil pasted across it to prevent any effect due to static charges on the glass. Another method of providing against such effects is due to Ayrton and Mather, who have invented a transparent *conducting* varnish which can be applied to glass, and which effectively prevents the accumulation of any charge upon it.

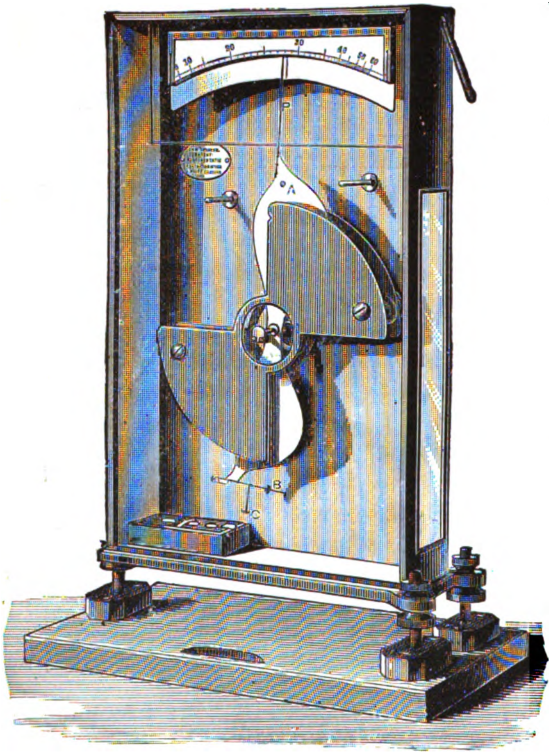


FIG. 222.—SINGLE VANE HIGH RANGE ELECTROSTATIC VOLTMETER.

The single cell and moving vane instrument, whilst perfectly satisfactory for high pressures, when used on low pressures does not produce sufficient torque to give any readable deflection, and it has therefore been found necessary to use a considerable number of cells and vanes in order to suit the instrument for ordinary low voltage work, and even then the lowest reading obtainable is of the order of 40 volts. Instruments in which use is made of a number of cells and vanes are known as "multicellular." An instrument in which two cells are used is that due to Ayrton and Mather. The fixed and moving parts are shown in Fig. 223.

The moving portion consists of an arm, through the centre of which passes the vertical spindle. At each end of the arm is fixed a vane of thin sheet aluminium, bent to form part of a cylinder, and these vanes move into two fixed cells which are also portions of cylinders. The spindle is mounted between jewelled centres, and the movement is controlled by a hair spring, the weight of the whole moving portion being less than 25 grains, so that the friction is exceedingly small. The case of the instrument is of metal, and shields the working parts from the effects of external charges. The lowest reading on the scale is 40 volts, but the scale is not divided into units until 90 volts is reached. Great attention is paid to the

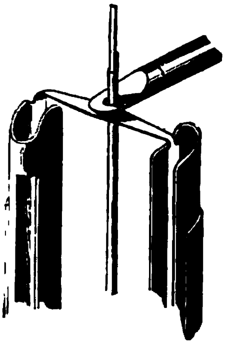


FIG. 223. — INDUCTORS AND VANES OF LOW VOLTAGE VOLTMETER.

insulation of the instrument, and it is fitted with fuses and a spark gap, so that if there is an excessive rise of pressure a spark leaps the gap and the fuses blow, detaching the instrument from the circuit.

Care should be exercised in handling electrostatic voltmeters as they act as condensers, and may remain charged and capable of giving a nasty shock for some considerable time after being removed from circuit. After disconnection the terminals should be connected together, and on some instruments a switch is provided to enable this to be done.

Another instrument, which is truly multicellular, is made by Messrs. Kelvin and James White of Glasgow. This instrument is portable, and very accurate, so that it is excellent for use as a sub-standard. Fig. 224 shows a plan of the instrument, the multicellular arrangement being the same in this as in the switchboard type which is clearly shown in sectional elevation in Fig. 225. The fixed portion consists of eleven shelves of metal, P P P, arranged one above the other so as to form 10 cells, C C C, on each side of the instrument, of either rectangular or triangular shape. In these 10 cells move 10 vanes V mounted on a spindle, which is suspended from a fine iridio-platinum torsion wire, passing up from the brass tube, T, and terminating in a torsion head for adjusting the zero. To the top of the spindle is attached a light aluminium pointer, I, which moves over a scale which is calibrated in volts. The moving vanes are connected to the case of the instrument, and also to two vertical guard plates, *g g*, which repel the moving vanes, whilst they are attracted by the fixed cells, thus exerting a large torque on the spindle.

The lower end of the spindle passes through a hole in the plate, and has a small nut attached which prevents it from being withdrawn. Between the upper end of the suspension wire and the torsion head is interposed a small bow-shaped spring to take up any shock which might otherwise injure the suspension.

When it is required to use the same instrument over a very wide range a multiplier is used. This merely consists of a non-inductive resistance, from which tappings are taken off at convenient places, which, of course, necessitates multiplying the voltmeter readings by a constant

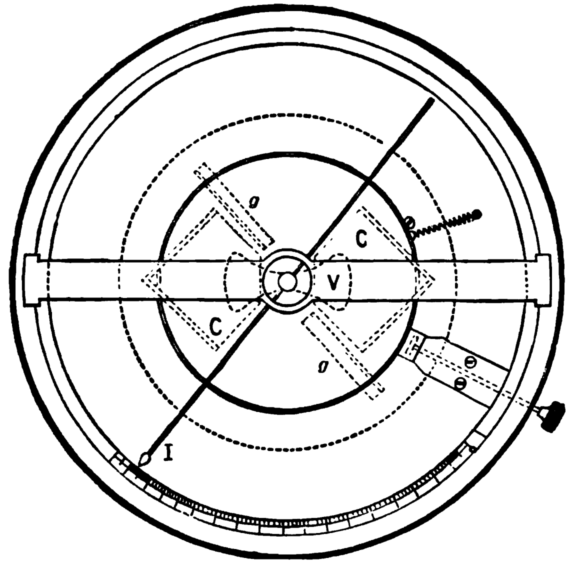


FIG. 224.—PLAN OF KELVIN'S MULTICELLULAR ELECTROSTATIC VOLTMETER.

whose value depends on the tapping used.

The instrument above described is chiefly used for laboratory work, but a modification of it suitable for switchboard use has also been put on the market. This is shown in Fig. 225.

The chief differences are that the end of the pointer is turned over, and moves along a cylindric vertical scale, which is easily visible, and that the end of the spindle is prolonged, and carries with it a vane which moves in an oil bath, thus providing the damping effect which is necessary to make the instrument dead beat.

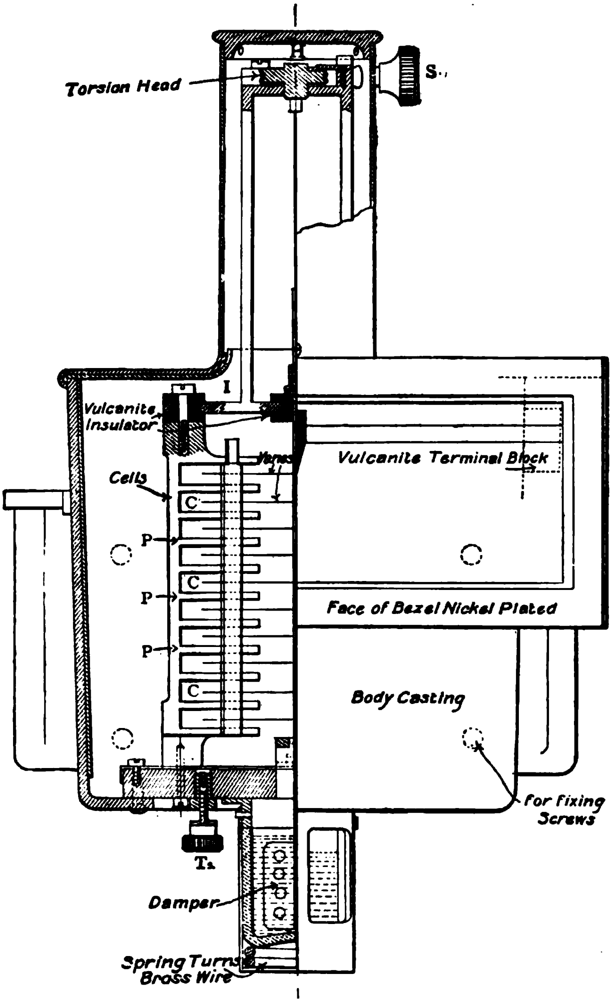


FIG. 225.—LORD KELVIN'S MULTICELLULAR SWITCHBOARD VOLTMETER.

CHAPTER IV.—ALTERNATING CURRENT MEASUREMENTS AND MEASURING INSTRUMENTS.

GENERAL PRINCIPLES—CURRENT AND POTENTIAL TRANSFORMERS—ADVANTAGES OF INSTRUMENT TRANSFORMERS—GENERAL THEOREMS—NECESSARY CONDITION OF ANY CIRCUIT — SIMPLE CIRCUIT — THREE - VOLTMETER METHODS — TWO - VOLTMETER METHODS—COMPLEX CIRCUITS (CURRENT)—COMPLEX CIRCUITS (POWER)—CONSTRUCTIONAL DETAILS—ERRORS—INDUCTION TYPE—SUMPNER'S INSTRUMENTS—PHASE-METERS—"IDLE CURRENT" AMMETERS—FREQUENCY METERS.

A LARGE variety of electrical phenomena have been selected as the working bases of electrical measuring instruments. Such phenomena may be broadly classified under the following heads :—

(*a*) Those applicable to continuous current instruments only ;

(*b*) Those applicable to both continuous currents and alternating current instruments ;

(*c*) Those applicable to alternating current instruments only.

(*a*) The first heading includes electrolytic devices, such as the ordinary voltmeter, and all polarised instruments, such as those of the D'Arsonval type.

In such instruments the force exerted on the movement is proportional to the current flowing, so that if the latter vary cyclically between positive and negative maxima about a mean zero value, the average force exerted on the movable system will be zero, and no indication will result.

(*b*) On the other hand if we so arrange the design that the force on the moving system is proportional at every instant to the square of the current flowing, the force will be unidirectional, since both $(-C)^2$ and $(+C)^2$ have only positive values.

Such a design would, to this degree, be suitable for an alternating current instrument. We have the square law illustrated in the following well known phenomena :—

(1) The heating effect of a current in a conductor.

(2) The force mutually exerted between a solenoid and a suitable iron armature.

(3) The force mutually exerted between two solenoids carrying the same or similar currents.

(4) The electrostatic force mutually exerted between two conductors at differing potentials.

All of these phenomena have been successfully adopted as the working bases of both continuous and alternating current instruments.

(*c*) Phenomena which depend on current variation can be made use of only in alternating current measuring instruments. They are usually distinguished by the appellation, "Induction Type" instruments.

We can thus subdivide alternating current instruments as follows :—

- Ammeters
    - Hotwire type
    - Dynamometer type
    - Electromagnetic type
    - Induction type
- Voltmeters
    - Hotwire type
    - Dynamometer type
    - Electromagnetic type
    - Electrostatic type
    - Induction type

Wattmeters
- Dynamometer type
- Electromagnetic type
- Electrostatic type
- Induction type

and also power factor indicators, wattless current ammeters, and a few miscellaneous devices of minor importance.

All alternating current measuring instruments may be said to fall under one or other of the above headings; other variations have been from time to time proposed and tried, such as electrostatic ammeters, hot wire wattmeters, etc. The scope of such devices is, however, so restricted that they can hardly be included in the category of commercial, test room, or even of laboratory instruments.

In a subsequent chapter we shall deal with the cyclic variations in the current and voltage of an alternating supply system, and we shall show that what we require an ammeter or voltmeter to measure is the square root of the mean square value of the current or voltage as the case may be. To this we have applied the term "virtual." We shall also show that, provided the cyclic variations be sinusoidal, the "virtual" value is equal to the amplitude of the sine wave divided by $\sqrt{2}$. We shall for the present denote instantaneous values of current and voltage by the letters c and v respectively, and the "virtual" values by C and V. We shall further shew, in Section VI., that the power in a circuit, or the mean value of the product cv, is, provided these factors be sine functions, equal to $VC \cos \phi$, where ϕ is the angle of phase difference between the current and voltage.

CURRENT AND POTENTIAL TRANSFORMERS.

Alternating instruments are not always directly inserted in or connected with the circuits in conjunction with which they are to be employed, but are more frequently connected through the medium of current and potential transformers. A current transformer, Fig. 226, is connected in series in the circuit just as an ammeter would be connected, while a potential transformer, Fig. 227, resembles a voltmeter in being invariably connected between the mains, or as a shunt to the main circuit.

In the first instance the current in the secondary is proportional to, and a facsimile of, the primary current, if we neglect that component of the latter which corresponds to the magnetising current of the ordinary transformer.

The graphical method of treating the theory of transformers (Section VI.) may be readily applied to the current or series transformer used in connection with measuring instruments.

Briefly, the conditions of equilibrium of the primary and secondary currents may be said to be as follows:—

Let the current in the secondary winding be C_2 and the number of turns n_2, the current and turns of the primary being denoted by C_1 and n_1 respectively. A certain E.M.F. must be induced in the secondary circuit in order to generate the current C_2 and overcome the resistance and self-induction, or impedance, of this circuit. Let the flux in the iron circuit of the transformer be F. This flux will be due to the resultant of the primary and secondary ampere turns or to $n_1C_1 + n_2C_2$ (remembering that $C_1 + C_2$ are vectors, and the above summation represents the vector sum, not the algebraic sum).

If we write S for the ampere turns necessary to produce the flux F (or magnetising ampere turns), we have the following relation between the three vectors.

$$n_1C_1 + n_2C_2 = S.$$

If now S may be taken as proportional to C_2 over the range for which the transformer is built, it will be observed that C_2

is directly proportional to C_1, in other words the ratio of transformation is independent of the load.

Where current transformers are used in conjunction with wattmeters this is a necessary condition, but if used with ammeters the above condition is desirable, though not essential, provided the ammeter be calibrated in conjunction with the particular current transformer with which it is destined to be used.

It is to be observed that the vector S is not truly proportional to C_2, so that in order to make the error thus introduced as small as possible it is necessary to keep the magnitude of S low in comparison with the value of n_2C_2 corresponding to the smallest value of C_2 required to be measured with accuracy.

To accomplish this it is obviously necessary to reduce the impedance of the secondary circuit to the lowest possible limit. Magnetic leakage in the secondary may be regarded as equivalent to a self-induction introduced into that circuit, and hence we see that it is of more importance to avoid magnetic leakage in the secondary of a current transformer than in the primary, a fact which has an important bearing on the best arrangement of primary and secondary winding in current transformers.

Summing up, we may say the essentials with regard to the design of series transformers for instrument work are :

(1) Low resistance of secondary circuit ;

(2) Low self-induction of secondary circuit ;

(3) Absence of magnetic leakage in secondary winding ;

(4) The normal full load ampere turns of primary or secondary must be large in comparison with their *vector* sum.*

No special remarks are needed here with regard to the theory of the potential transformer as shown in Fig. 227. The conditions which govern the drop of voltage in the secondary of such a transformer are indicated in Section VI.

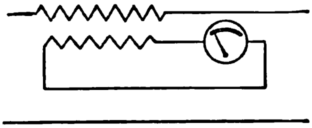


FIG. 226.—CIRCUITS OF "CURRENT TRANSFORMER."

Here again, for wattmeter purposes it is essential that the ratio of transformation should not be dependent upon the secondary load, while this condition is not necessary (though desirable) when such transformers are used in conjunction with voltmeters, provided the two are calibrated together as previously explained.

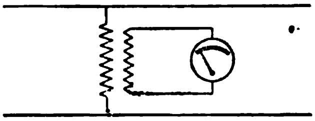


FIG. 227.—CIRCUITS OF "POTENTIAL TRANSFORMER."

ADVANTAGES OF CURRENT AND POTENTIAL TRANSFORMERS.

The advantages gained by the use of such transformers are manifold :—

(1) The measuring instruments are entirely unconnected electrically with the circuit, one terminal of each instrument may therefore be earthed ; hence, although the main circuit be one of high potential, the instruments may be handled with impunity and, if desired, removed from the circuit for repair.*

---

* It is to be noted that the primary and secondary ampere turns are very nearly in opposite phase, so that their vector *sum* may readily be a small quantity in comparison with either.

* Before removing an ammeter the secondary circuit of the transformer must be short circuited, and must remain in that condition so long as

(2) In the case of voltmeters and wattmeters for high potential circuits the necessity for large non-inductive or other resistance is avoided. These are cumbersome to use, delicate to handle, and a source of trouble and inconvenience.

(3) In the case of ammeters for heavy current circuits, only a relatively small current need be introduced into the instrument itself, rendering it simpler and cheaper to manufacture, and easier to manipulate.

(4) Manufacturers may adopt a standard winding for all ammeters and voltmeters, the scale of the instrument and the winding of the transformer alone being modified to render the combination suitable for use in any circuit. The combination with the instrument is such that the pointer indicates the conditions obtaining in the primary circuit, and not the secondary.

For example, an ammeter and a voltmeter might be required for an 80-ampere 2,000 volt feeder circuit. An ammeter graduated 0–100 amperes, supplied with a 10-ampere winding (or one such that with 10 amperes the full scale deflection would result), used in conjunction with a 10 : 1 current transformer, would be suitable. The potential transformer might have a 20 : 1 ratio, the voltmeter having a 100 volt winding.

GENERAL THEOREMS.

Before proceeding to describe constructional details of various measuring instruments, it will be advisable to continue the theoretical considerations of a few general theorems on the use of instrument transformers and instruments in single and complex circuits.

A "single" circuit is one possessing two lines, current going out from the generating source by the one, and returning by the other. If the circuit be an alternating current one it is called a single-phase circuit. We know that ***at every instant*** a current returns by the one line equal to that leaving the generator by the other. If we take as a positive direction of flow of current a flow away from the source of generation, we can express the above condition by saying the sum total of the outward flow of current is zero at every instant, or merely, having regard to the algebraic sign, the sum total current flowing in the two lines is zero.

Complex Circuits.—Instead of only two lines leaving the generating source we may have three or more, and the currents in these may have all manners of phases and frequencies. A complex circuit may be defined as one consisting of more than two lines leading away from the generating source. As simple examples of complex circuits may be instanced a three-wire continuous current circuit, and a three- or four-wire two- or three-phase circuit.

It would, of course, be quite feasible to consider all these various types of circuit separately, but it will be more convenient to consider the general case, and then the above enumerated types as special cases.

NECESSARY CONDITION OF ANY CIRCUIT.

In Fig. 228 let *a*, *b*, *c*, *d*, *e*, represent any system or combination of generators, either alternating current or continuous current, and of same or differing frequencies. The only lines outgoing from this mesh are 1, 2, 3, 4, 5, carrying currents whose instantaneous values are C_1, C_2, C_3, C_4, C_5, (current flowing away from network being reckoned positive). We have then the condition $C_1+C_2+C_3+C_4+C_5=0$, which is necessarily true, this being merely a statement of the fact that as much electricity returns to a generator or group of generators as leaves

the ammeter remains unconnected. The voltmeter is removed in the ordinary way. The similarity of treatment with that accorded to continuous current ammeters and voltmeters will be at once apparent.

it. For example, if we were to suppose the sum to be a negative quantity, this would mean that a larger current was flowing towards the generating source than away from it, in other words that electricity was being accumulated or was being destroyed within the generator network.

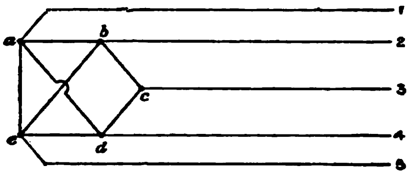
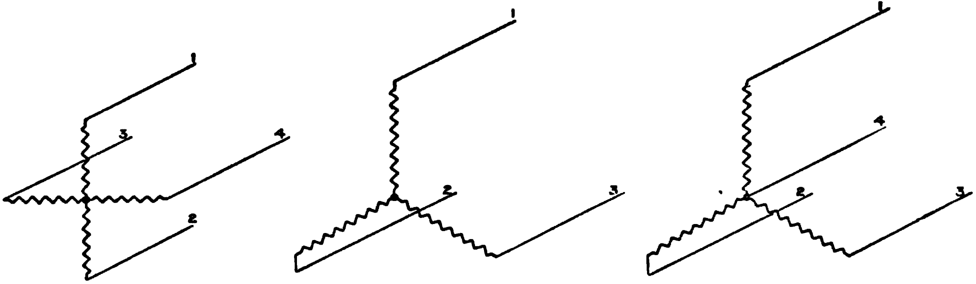


FIG. 228.

This is the only necessary relation in a complex circuit: for instance, C_1 might be a continous current, C_2 an alternating current of 100 volts, C_3 might be zero, C_4 might be aperiodic; but given these entirely arbitrary and unrestricted functions C_5 is restricted, its value being—$(C_1+C_2+C_3+C_4)$. In Fig. 229, (*a*) represents a four-wire two-phase system and $C_1+C_2+C_3+C_4=0$, (*b*) represents a three-wire three-phase system, and $C_1+C_2+C_3=0$ at every instant. If the neutral point be earthed (*c*) so that current may flow by this connection the former condition, is no longer necessarily true, but we must write $C_1+C_2+C_3+C_4=0$.



(*a*) (*b*) (*c*)

FIG. 229.

MEASUREMENTS IN SIMPLE CIRCUIT.

We have already pointed out that the phenomenon chosen as the working basis of an alternating ammeter or voltmeter must involve the square law, that is that the force on the moving system must at every instant be proportional to the square of the current flowing. The mean force which determines the position the needle will occupy is thus proportional to the mean square value of the current or voltage as the case may be, and clearly if the instrument be graduated with a square root scale the indication will be proportional to the square root of the mean square value, *i.e.* the "virtual value" of current or voltage.

We will now show how voltmeter and ammeter readings may be taken to determine the watts in a single circuit. Various methods have been devised with this object, but they may all be said to be based upon one or other of the following algebraic identities.

$$(1)\quad \frac{(kv+rc)^2-(kv)^2-(rc)^2}{2\,ks}=vc$$

$$(2)\quad \frac{(kv)^2+(rc)^2-(kv-rc)^2}{2\,kr}=vc$$

$$(3)\quad \left\{\frac{(kv+rc)^2-(kv-rc)^2}{4\,kr}\right\}=vc$$

THREE-VOLTMETER METHODS.

Let M, Fig. 230 (*a*), represent a motor the power supplied to which is to be measured. In series with the motor is inserted a non-inductive resistance *r*; three voltmeters 1, 2, 3, are connected, 1 across the terminals of the motor, and indicates the square root of the mean value of v^2; 2 across the non-inductive resistance measures the square root of the mean value of $(rc)^2$; while the potential difference at the terminals of 3 is the sum of rc and v at every instant. Hence this voltmeter indicates the square root of the mean value of $(v+rc)^2$. Now the watts supplied to M, which is the mean value of vc, is by identity (1), putting $k=1$, proportional to the mean value of $(v+rc)^2-v^2-(rc)^2$. But the mean value of this expression is the same as the mean value of $(v+rc)^2$ – mean value of v^2 – mean value of $(rc)^2$, and these are precisely the values the three voltmeters measure, although their scales are graduated to indicate the square roots of these values. Hence if v_1, v_2, v_3, are the voltmeter readings respectively we have.

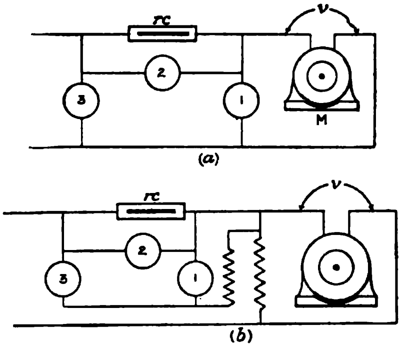


FIG. 230.—DIAGRAMS OF THREE-VOLTMETER METHODS OF POWER MEASUREMENT.

$$\frac{v_3^2-v_2^2-v_1^2}{2r} = \text{mean value of } vc.$$

Hence, knowing r we can determine the value of the watts supplied to M from the three voltmeter readings.

One great disadvantage of this method is that, in order to secure accuracy, the voltage v_3 must be of the same order as v_1; this means first that a large amount of power may have to be absorbed in the non-inductive resistance, which is a great drawback, and secondly, that the test cannot be conducted without providing a circuit of very much higher voltage than that for which the motor or other machine is designed.

To overcome these difficulties the modification shown in Fig. 230 has been suggested. In this case the voltage, v, is transformed down to a small value, say, of the order of two volts or less, and voltmeter 1 now measures the virtual value of kv where k is the reciprocal of the transformation ratio. The voltage drop in the non-inductive resistance can now be reduced to the order of one or two volts, so that it is no longer necessary to provide a special circuit for the test, or to absorb a large amount of power in the resistance. This method allows a motor to be tested *in situ*. It must be noted that the watts lost in the transformer are included in the measurement, and care must be taken that this is a negligible quantity, or a suitable correction must be made.

TWO-VOLTMETER METHOD.

If $2\,kv$ be the voltage induced in the secondary of the transformer, then the potential difference across the one voltmeter will be $(kv+rc)$ and across the other $(kv-rc)$; the difference between the mean squares of these values is the mean value of $4kr \times vc$, hence

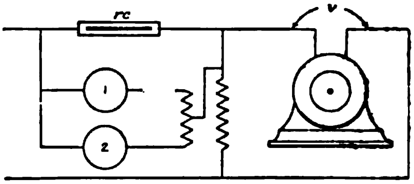


FIG. 231.—TWO-VOLTMETER METHOD OF POWER MEASUREMENT.

$$\frac{v_1^2-v_2^2}{4kr} = \text{watts.}$$

Other methods or connection will be at once obvious which supply a *physical inter-*

pretation to the *purely algebraic identities* before mentioned.

CURRENT MEASUREMENTS IN COMPLEX CIRCUITS.

In Fig. 232 let 1, 2, 3, 4, represent a complex circuit, a current transformer being inserted in each line. For the present suppose the ratio of each transformer is 1 : 1. The secondary of each transformer is closed through an ammeter and the short circuiting link *a*, *d*, *b*, the current in each secondary is therefore equal to that in the corresponding primary. Let c^1 be the total current flowing in the link *a*, *b*, *d*, then since c_1, c_2, etc., and c^1 all meet at the point *a*, and no accumulation of electricity can occur here, we have

$$c_1+c_2+c_3+c_4+c^1=0.$$

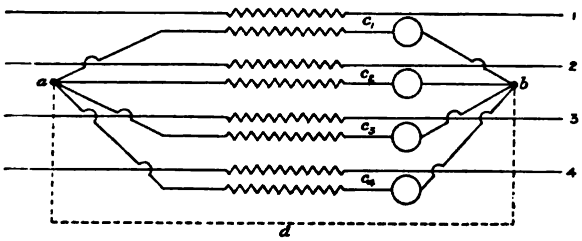


FIG. 232.—COMPLEX CIRCUIT.

But the necessary condition of the complex circuit is that

$$c_1+c_2+c_3+c_4=0.$$

Hence $c_1=0$, *i.e.* no current will flow in the link *a*, *d*, *b*, and its presence is unnecessary.

[It must be kept well in mind, throughout these arguments, that electricity behaves as an incompressible fluid ; so, also, must the relation between current and quantity, viz. that *current* is *rate of flow of electricity*.]

Let us now dispense with the transformer in any one line, say line 4, removing the secondary circuit entirely.

We have now the conditions :—

$$c_1+c_2+c_3+c^1=0$$
$$c_1+c_2+c_3+c_4=0$$

hence $c^1=c_4$; in other words, if we omit one secondary circuit, but insert an ammeter in the link, the reading of this ammeter will be the current in the branch or line containing no transformer.

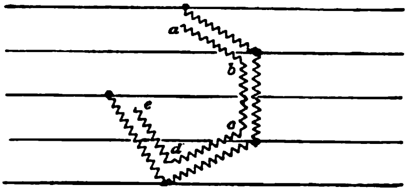


FIG. 233.—VOLTAGE MEASUREMENTS IN COMPLEX CIRCUIT.

Hence, generally, if we have *n* lines, we can measure the current in each simultaneously with *n* - 1 transformers.*

Again if we consider a complex circuit having *n* lines, the number of voltmeter measurements possible by connecting a voltmeter between any two lines, is equal to the number of combinations possible with *n* things taken two at a time or $\frac{n(n-1)}{2}$. All these measurements are clearly possible if we connect *n* - 1 transformers between the lines.

Fig. 233 represents a complex circuit of five lines. The total number of voltages taken between lines is ten. If we connect four transformers (with the same ratio) as shown, these ten voltages may be measured in miniature by suitably connecting a voltmeter between two of the points *a*, *b*, *c*, *d*, *e*, which form the secondary terminals of the transformers.

---

* It must be remembered that although the sum of the instantaneous values of line currents is zero at every instant, the sum of the virtual currents is not zero. For example, the three line-currents in a symmetrical three-phase system will be equal as shown by ammeters, although their instantaneous sum is, as stated, zero at every instant. It is not possible to determine the virtual value of the n^{th} line current in a system, as above, even though we know the values of the $n-1$ virtual currents, except by direct measurement.

As an example of the foregoing theorems Fig. 234 shows three ammeters and three voltmeters connected in a three-phase circuit to indicate the three-phase voltages and currents by means of two current and two potential transformers.

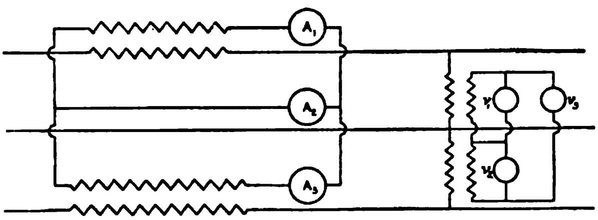


FIG. 234.—CURRENT AND VOLTAGE MEASUREMENTS WITH THREE INSTRUMENTS AND TWO TRANSFORMERS.

POWER MEASUREMENTS IN COMPLEX CIRCUITS.

In Fig. 235 a complex circuit of five lines is represented. Power is generated in the five branches meeting at o. The voltages generated and the currents flowing in these branches are v_1, v_2, etc., c_1, c_2, etc. (instantaneous values).

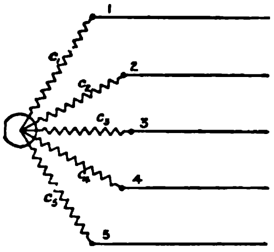


FIG. 235. POWER MEASUREMENT IN COMPLEX CIRCUIT.

Let us treat the potential of o, as our datum of reference, or zero of potential, then the instantaneous values of the potentials at the points 1, 2, 3, 4, 5, are v_1, v_2, etc. The total power is (instantaneous) $v_1 c_1 + v_2 c_2 + v_3 c_3 + v_4 c_4 + v_5 c_5$.

But $v_5 (c_1 + c_2 + c_3 + c_4 + c_5) = 0$ is a necessary condition of the complex circuit; hence

$$(v_1 - v_5)\, c_1 + (v_2 - v_5)\, c_2 + (v_3 - v_5)\, c_3 + (v_4 - v_5) c_4 = 0.$$

This being true for instantaneous values it similarly holds for mean values, that is to say that four wattmeters* suitably connected will give us the total power in this complex circuit. Hence, generally, (n—1) wattmeters connected to a circuit of n lines will give the total power transmitted.

Examining the above expression we see that $v_1 - v_5$ is the potential difference between the points 1 + 5, $v_2 - v_5$ the potential difference between the points 2 + 5, so that to obtain the total power we insert the series coils of the (n - 1) wattmeters in n - 1 of the lines and connect each potential coil between the n^{th} line and that line in which the corresponding series coil is inserted. The total power is the sum of all the individual readings. Fig 236 shows two wattmeters connected to a three-phase circuit, the total power being the sum of the readings of the two wattmeters.

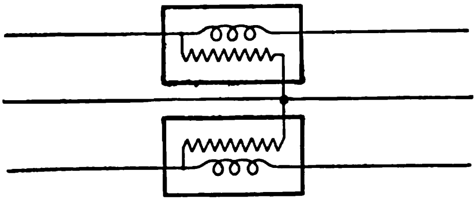


FIG. 236.—TWO WATTMETERS MEASURING THREE-PHASE POWER BY THEIR SUM.

We see further that if the neutral point of the three-phase system be earthed, and current flow in this earth connection, we must consider this a four-wire circuit, hence three wattmeters are needed to measure the total power.

The readings on the two wattmeters, Fig. 236, will be the same if the system be symmetrical, and there be no phase displacements of the line currents relative to the respective phase E.M.F.s, but if this be not so, the readings on the two meters will in general differ, and it is even possible for the one to be negative. The foregoing theorems are applicable to any complex circuit with any system of E.M.F.s and currents; thus we might apply them to a five-wire continuous current distribution system as well as to a three-phase alternating current system with unbalanced loads. The methods employed are advantageous since they avoid all reference to phase relations in alternating current circuits.

---

*At the present moment we consider a wattmeter as any instrument having a potential coil and a main current coil so related that the reading on the instrument is the mean value of the product of the potential difference at the terms of the potential coil and the amperes in the main current coil.

We will now consider another method for the measurement of power in a three-phase circuit, which is only applicable to such a circuit.

The instantaneous power in this circuit is

$$v_1c_1+v_2c_2+v_3c_3,$$

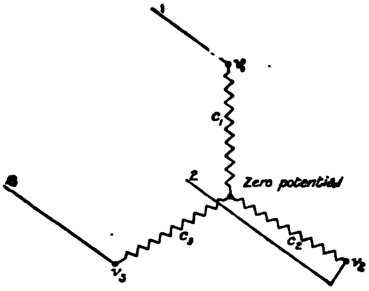


FIG. 237.

or, what is the same thing,

$$\tfrac{3}{2}\, v_1c_1 - \tfrac{1}{2}\, v_1c_1+v_2c_2+v_3c_3$$

Now we may write $c_1 = -(c_2+c_3)$
$v_1 = -(v_2+v_3)$

The first is the necessary condition where three currents meet at a point, and is therefore not applicable solely to a three-phase system but generally; the second condition is by no means generally true, but is true in the case of a symmetrical three-phase supply voltage (*i.e.* where the virtual voltage per phase is the same, and these three voltages are 120° apart).

Hence, in the case of a three-phase supply voltage only, we can replace the expression $\frac{1}{2}v_1c_1$ by $\frac{1}{2}(c_2+c_3)(v_2+v_3)$ whence we have:

$$v_1c_1+v_2c_2+v_3c_3 = \tfrac{3}{2}v_1c_1+\tfrac{1}{2}(v_2-v_3)(c_2-c_3),$$

and the watts, or the mean value of the left-hand expression, equal the mean value of the expression on the right-hand side. Now the mean value of $\frac{3}{2}v_1c_1$ can be directly obtained from a wattmeter inserted in phase 1 in the ordinary manner, while the mean value of $(v_2-v_3)(c_2-c_3)$ may be directly obtained by wattmeter measurement, if we can insert the series coil in a circuit in which the current c_2-c_3 flows at every instant and connect the potential winding of the wattmeter between the lines 2 and 3. The current c_2-c_3 is readily obtained by means of series transformers inserted in the branches 2 and 3 respectively.

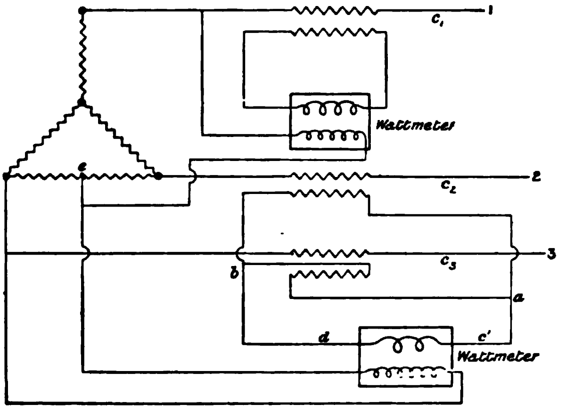


FIG. 238.—TWO WATTMETER MEASUREMENT OF THREE-PHASE POWER, INDICATING BALANCE ALSO.

There is merely a resistance choking coil, or something else connected between 2 and 3 to give us the potential which exists at *e*.

Let us insert series transformers in lines 2 and 3. For the sake of simplicity we suppose the ratio of transformation unity. The series coil of one wattmeter is inserted in the low resistance link *a*, *d*, *b*. The secondary of transformer 3 is reversed. If c^1 is the current in the link we shall have $c_2 - c_3 + c^1 = 0$, since these three currents meet at the point *a*; hence

$$c^1 = c_2 - c_3.$$

The voltage supplying the shunt winding of this same wattmeter is $\frac{1}{2}(v_2 - v_3)$.

With regard to the wattmeter inserted in branch 1, we see that the current in the main coil is c_1, while the potential difference across the shunt coil, which is connected between 1 and the point *e*, will readily be seen to be in the case of a three-phase supply $\frac{3}{2}v_1$, hence the sum of the the two wattmeter readings gives the total power.

It may be further noted that if the system be balanced, though inductive, the total power is $3v_1c_1$; in such a case the wattmeter in phase 1 would read one half of this power, and consequently both wattmeters would record alike. This arrangement then possesses an advantage over the one previously described in that it not only gives the total power, but gives also an indication as to whether the system is balanced or not. As was pointed out in the previous method the wattmeters do not read alike, even though the system be balanced, unless the current in each line is in phase with the corresponding leg voltage.

It is however to be observed that whereas the previous method is applicable generally to a three-line circuit without restriction, the method just described is restricted to a symmetrical three-phase supply voltage.

It is obvious that the total power in a complex system can depend only upon the currents and voltages in the various lines, and in no way involves the formation or grouping of the generator system. An infinite number of totally distinct and different generator systems may produce exactly the same currents and voltages in the various lines of the complex circuit, in which case each generator system would be supplying the same total power to the circuit. It follows, therefore, that there are an indefinite number of ways of combining wattmeters to measure the power in a given circuit. Let $v_1\ v_2\ .\ .\ v_n$ be the potentials of *n* lines forming a complex circuit reckoned above any arbitrary zero of potential, let $c_1\ c_2\ .\ .\ c_n$ be the corresponding currents in the lines.

We have shown that the power is $(v_1 - v_n)\,c_1 + (v_2 - v_n)\ c_2\ .\ .\ (v_{n-1} - v_n)\ c_{n-1}$ now $(v_n - v^1)\ (c_1 + c_2 +\ .\ .\ c_n) = 0$, since the sum of the line currents is necessarily zero, v^1 is the potential of any point, whether a point of the generator system or not. Adding, we have

$$(v_1 - v^1)\ c_1 + (v_2 - v^1)\ c_2 + \text{etc.}$$
$$+ (v_{n-1} - v^1)c_{n-1} + (v_n - n^1)\ c_n$$

for the total power.

Let us take *n* wattmeters and connect the series coil of one wattmeter in each line, connect one end of the shunt winding to the same line, and connect all the other ends of the shunt windings together. Let us call the potential of this common point v^1, then the wattmeter in line 1 will read the mean of $(v_1 - v^1)\ c_1$, and so on for the

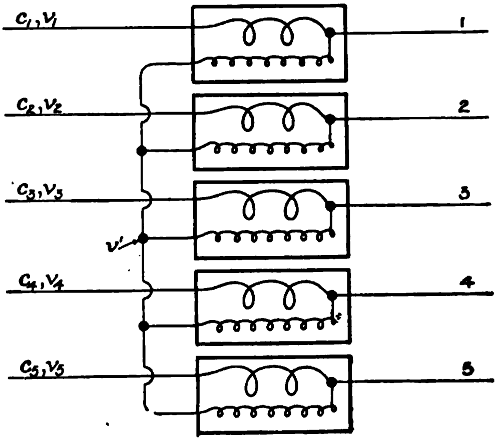


FIG. 239.—POWER MEASUREMENT IN COMPLEX CIRCUIT.

others. It is thus clear that with n wattmeters we can find the total power in a complex circuit of n lines by connecting them as shown, and that it is quite immaterial what value v^1 may have. For example, it may have the natural value which accrues from the connections as shown, or it may have a forced value, such as zero, by being connected to earth, or the point taken as datum of potential, or it may have a forced value by being connected to some one point of the generator system.

In practical work it is sometimes found advantageous to employ three wattmeters for power measurements in a three-phase circuit instead of two, as the potential across the shunt windings is less in the first case, thus avoiding in special cases the necessity for potential transformers. In such cases it is important to remember that it is not by any means essential to connect the shunt windings to the neutral point of the system, as we have just seen.

MODIFIED CONSTRUCTION FOR ALTERNATING CURRENTS.

Broadly speaking, where the principle employed is suitable (*see* p. 283) instruments intended for use on continuous current circuits will work on alternating current circuits. In most of such instruments, however, the readings will be inaccurate unless the scale is re-marked, and sundry constructional matters need attention. The two most obvious changes to be made are the splitting of the bobbins if of metal and the lamination of the iron if it be present in any considerable mass. If the bobbin on which the coil is wound be of metal, it must be split by a saw-cut through both flanges and the body, to prevent the circulation of induced currents in a direction parallel to the current in the windings; the bobbin would act, in fact, like a short circuited transformer secondary of one turn, the winding constituting the primary.*

The iron, if in the form of a thin sheet or of a wire of very small diameter, need not be laminated; but larger bodies of iron must be, to prevent eddy currents. The effect of hysteresis, which in an instrument used with continuous currents makes the reading depend slightly on the relative magnitude of the current used immediately before and on the direction of the current, is somewhat obscure when alternating currents are used. During the periods ot decreasing values of current the effect is to make the readings higher than if no hysteresis were present, until the current passes through zero. From the instant at which the current passes through zero until the magnetism also reverses, the effect is to produce lower readings, and this effect persists until the rising branch of the curve of reversed magnetism reaches the same value at any current that it would have had with virgin iron. Whether the deflection is, as a whole, increased or decreased, depends upon the shape of the hysteresis curve and upon the wave form of the current. The results for one case are given in Fig. 240.

VOLTMETER ERROR.

The indication of a voltmeter is modified by the fact that the current through it at a given voltage is no longer of the magnitude given by the expression $\frac{E}{R}$, but is reduced by the self induction to the magnitude of

$$\frac{E}{\sqrt{R^2 + p^2 L^2}},$$

In order to make temperature error small, it is usual, as we have seen, to put a resistance of negligible temperature coefficient in series with the winding proper, which is of copper. The better this compensation the larger the ratio of the series resistance to the resistance of the winding. It is a very simple matter to make this resistance non-inductive, and in such cases the error due to self induction in the winding can be made quite small. Below are given the results of tests of a number of moving iron instruments of various patterns at several frequencies and with continuous currents (page 300).

---

* This chapter presumes some knowledge in the reader of alternating current phenomena, and the following Section may be read with advantage before this chapter.

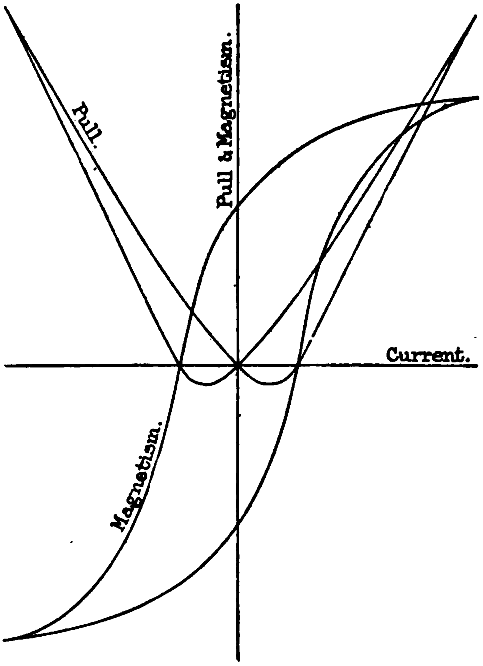


FIG. 240.—CURVES SHOWING EFFECT OF HYSTERESIS ON THE RELATION BETWEEN CURRENT IN COIL AND PULL ON IRON.

WATTMETER ERROR.

The wattmeter error is the most difficult of all to eliminate, and yet is in many cases of great importance. The error arises from the fact that the current in the voltage coil is out of phase with the voltage producing it, and is dependent in magnitude upon the frequency. The errors are thus due to just the same causes as those in a continuous current voltmeter used for alternating currents; the magnitude of the secondary is, however, greater since a series resistance of equal relative proportion cannot be employed, owing to the great difficulty of getting sensitiveness, which demands many turns of fine wire in the winding. The action of a wattmeter may be regarded as due to the neutral action upon each other of a magnetic field due to the voltage of, and one due to the current in, the circuit; hence it will be easily seen that, if the current in the voltage coil lags, the "voltage magnetism" lags, and the effect on the reading depends upon whether the current in the main coil lags behind the voltage or not, and by what amount. If not at all, then the "current magnetism" and "voltage magnetism" are out of step with each other, although the voltage and current are not, and the deflection is less than it should be; if the current in the main coil lags behind the voltage by the same amount as the voltage current in the shunt coil does, the fluxes are in step, and the maximum deflection is produced (for those amperes and volts) which is greater than it should be with a lagging current. If, further, the main current lags more than this the reading is still too high. The full explanation of this error is deferred until vector diagrams have been described in Section VI., and an expression for the magnitude of the error is there given.

INDUCTION INSTRUMENTS.

Instruments of this type, such as shown in Fig. 241, depend for their action on the induction of currents in a movable disc by a fixed coil carrying an alternating current. The field is provided in a rather narrow air gap left in an iron core of horse-shoe or circular shape, on which is wound the coil. The edge of the disc plays in the gap, the disc being pivoted so as to run freely in it, and the direction of the field, therefore, at right angles to the plane of rotation. If the disc were perfectly symmetrical the forces between the induced currents and the field would balance in directions which are symmetrical to the field and axis of rotation. The field is applied to the edge of the disc for obvious reasons and hence the tangential forces, which are the only ones to produce rotation, would balance each other. The disc is therefore shaped, either as regards its thickness from face to face, or is cut away at its periphery, or so as to make the central portion open, so that the induced currents have not an equally good path all over the disc. The difference in the resistance of the various paths occasions, of course, a difference in the magnitude of the currents traversing them, though the induced E.M.F. be the same. The portions carrying the heavier currents experience a greater force of repulsion* than those with smaller currents, and hence tend to move out of the field more strongly than do the latter, and under this difference of forces the disc begins to rotate. Control is provided by a hair-spring or balance weight and the movement of the disc ceases when the propelling force and the force of restitution due to the control are equal. This last depends on the position of the disc, and the former on the magnitude of the current in the winding ; the position of balance at which the disc comes to rest is thus a measure of the current in the coil. In the case of a voltmeter, the current in the coil is, of course, in turn a measure of the voltage at its terminals.

The instrument is essentially dead beat in its action, and a glance at the scale shown in Fig. 242 will give some idea of the pleasure of working with such instruments.

The chief source of error lies in variation in the frequency from that at which the instrument was standardised. The induced voltage in the disc is clearly proportional to the frequency so that the difference in the tangential forces also varies with the frequency, and an ammeter reads too high on a higher, and too low on a lower, frequency than it is calibrated with. If a voltmeter has little or no non-inductive resistance in series with its coil, it is doubly susceptible to frequency error, since the magnitude of the inducing field as well as its frequency is affected by the frequency of supply (*vide supra*).

The wave form of current or voltage affects these instruments to a minor degree.

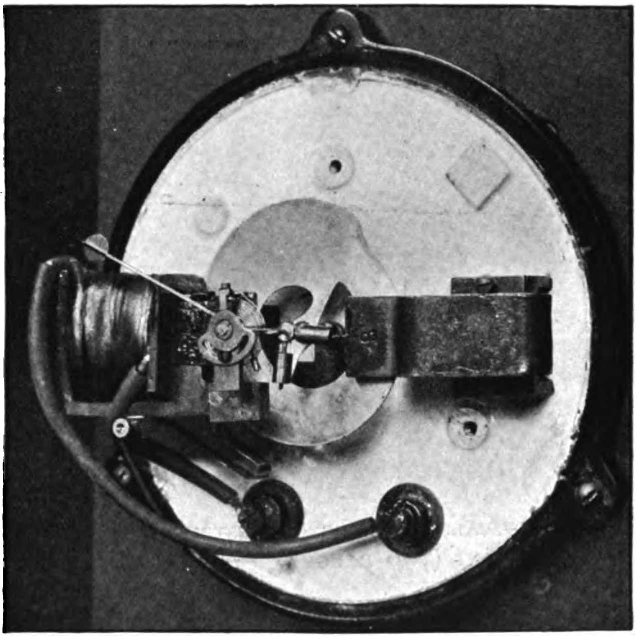


FIG. 241.—INDUCTION INSTRUMENT.

---

* *See* Section VI.

An instrument which is also only of service on an alternating current circuit, and whose boldness of design has broken entirely new ground is

DR. SUMPNER'S WATTMETER.

As has already been pointed out, the employment of iron in direct current wattmeters is inadmissible on account of the variation in permeability, in consequence of which the field produced by the coil wound round the iron will not be proportional to the current producing it, with the result that the mutual force acting between that field and any other field is not proportional to that current. Further, the hysteresis of the iron interferes with the accuracy of the readings if the current round the coil be reversed.

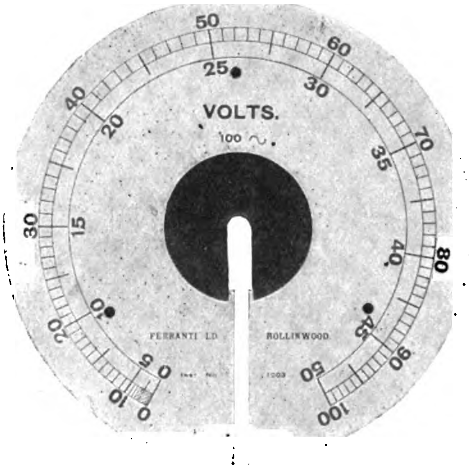


FIG. 242.—SCALE OF INDUCTION INSTRUMENT (TWO RANGE).

In alternating current instruments the same objections hold good, with the additional trouble that eddy currents are induced which re-act upon the magnetising coil and upon the field, and there are frequency errors also. The absence of iron, however, in wattmeters makes it exceedingly difficult to design an instrument which shall be reasonably economical in its voltage coil, and which shall yet produce a sufficiently strong field to make a sensitive and accurate instrument. Further, if a strong field be produced the self-induction at once causes the field to lag behind the impressed voltage, tending to make the instrument inaccurate and in effect useless. In Dr. Sumpner's instrument this peculiarity, instead of being made a trouble of, is turned to good advantage, and, in fact, he so designs his instrument that the voltage coil shall have as large a self-induction as possible compared with the resistance of its winding. By this means a field is produced which may fairly be considered at every instant to be lagging strictly 90 degrees behind the impressed voltage. It would, of course, be useless to put a current which is in phase with the current of the circuit to be metered through conductors in such a field, since, when the power factor is unity, there would be between the conductors and the field no total force tending to produce a deflection. To overcome this obstacle Dr. Sumpner boldly makes arrangements for supplying the conductors with a current that shall also lag 90 degrees behind the circuit current. This he does by means of a so-called current transformer, which he further carefully designs so as to have a comparatively large air gap, and therefore a magnetic circuit of practically constant permeability. With such a transformer the magnetic flux will be proportional to, and in phase with, the current producing it, and the secondary windings thus become the seat of an E.M.F. lagging 90 degrees behind, and proportional to the primary current. The secondary E.M.F., if the power factor being metered is unity, is therefore exactly in phase with the magnetic flux produced by the voltage coil of the wattmeter, and if that secondary E.M.F. produces a current in phase with itself, through conductors placed in the field, there will be forces between them to give deflections on the wattmeter truly proportional to the watts in the circuit. It is clear that these deflections will be due to the product of one quantity which is proportional to the rate of change of the voltage, and another quantity which is proportional to the rate of change of the current at every instant. The product of these two quantities is itself a measure of the power, as Dr. Sumpner has pointed out, the proof being as follows:—

Let the various quantities involved be denoted as follows:—

E = voltage of the circuit whose power is to be measured.
C = current in the circuit whose power is to be measured.
N = flux in the voltage coil of the instrument.
s = number of turns in the voltage coil of the instrument.
r = resistance of the voltage coil of the instrument.
i = current in the voltage coil of the instrument.
R = resistance of secondary circuit of the current transformer.
c = current in this circuit.
τ = the periodic time.

Then

$$(1) \qquad E = s\frac{dN}{dt}10^{-8} + ri.$$

$$(2) \qquad c = -\frac{k}{R}\frac{dC}{dt}.$$

Where k is the value of the secondary voltage of the current transformer for unit rate of change of primary current. Now ri is assumed to be negligible (p. 296), and c is assumed to be so small as to not interfere with the truth of (2). The torque on the moving coil is clearly

$$\frac{1}{\tau}\int_0^\tau c\,N\,dt,$$

which may be rewritten

$$\frac{1}{\tau}\frac{k}{R}\int_0^\tau \frac{dC}{dt}N\,dt.$$

But where C and N are periodic functions having the same period, this last integral is numerically the same as

$$\frac{1}{\tau}\frac{k}{R}\int_0^\tau C\frac{dN}{dt}\,dt;$$

but by (1) $\frac{dN}{dt} \propto E$, ri being negligibly small, whence the torque may be written

$$k_1\int_0^\tau C\,E\,dt,$$

where k_1 is a constant involving k, R, s, and τ. Thus the torque is proportional to the true watts.

The advantage of these arrangements is that an exceedingly sensitive as well as accurate instrument can be produced, the chief points in the design being the arrangement of the magnetic circuit and the coil upon it, so that the ir drop in that coil shall form a truly negligible proportion of the total voltage at the ends of the coil, and further the arrangement of the moving coil circuit in such a way as to to be practically non-inductive, with the result that the current in it is, to all intents and purposes, truly in step with the secondary E.M.F. of the current transformer.

PHASE METERS OR POWER-FACTOR INDICATORS.

The function of these instruments is clearly denoted by their name, but they are not ordinarily constructed to indicate any difference of phase other than one existing between a pressure and a current. All ordinary instruments of this type have two coils mounted on a spindle in such a way that they can rotate in the field produced by a third coil. In some instances the movable system carries three coils, this type of instrument being particularly adapted to three-phase circuits, while the former is designed for single-phase work. The fixed coil carries the current, and the movable coils currents determined by the voltage or voltages whose phase-relation to the current in the fixed coil is to be determined. The connections of two such instruments, made by Messrs. Everett, Edgcumbe & Co., are shown in Figs. 243 and 244. In the single-phase instrument the two movable coils, *a*, *b*, are set at right angles to one another on the spindle, while in the instrument intended for a balanced three-phase circuit the three, *a*, *b*, *c*, are set with their axes 120° apart. It will be seen that the effect of these three coils is to produce a rotating field (*vide* Section VI.), while the fixed coil, C, produces merely an oscillating field. Under these conditions there arises a tendency for the movable system to take up a definite position with regard to the fixed coil; the position is such, that at the moment of maximum field due to the fixed coil, the field due to the movable system, when at its maximum, coincides in direction and sense with that of the fixed coil. When the field due to the movable system has rotated through half a revolution, that due to the fixed coil will have reversed and be again at a maximum, and the forces between the fixed and movable systems, due to their fields, will give rise to a stable condition so long as their time relations are unchanged. If now for some reason the phase of the current in the fixed coil is retarded, the position of the movable system will be readjusted, in order that its rotating field, which continues to rotate at the same rate as before, may again coincide with the other field (when at a maximum) in time and position.

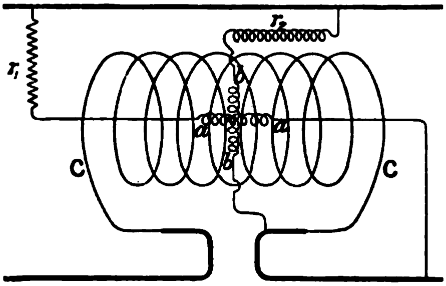


FIG. 243.—CONNECTIONS OF A MONOPHASE POWER-FACTOR INDICATOR.

If the instrument is to indicate these positions clearly, the moving system must be either entirely free of control by gravity or spring, or subject only to an extremely weak control, which will merely prevent any undesirable oscillation of the needle.

The single-phase instrument shown really operates on identically the same principle, for the two fixed coils are so connected by means of a resistance, r_1, and an inductance, r_2, that they carry two currents which are largely displaced in phase as regards one another. They may, therefore, be regarded as producing a rotating field, just as does the stator of a two-phase motor.

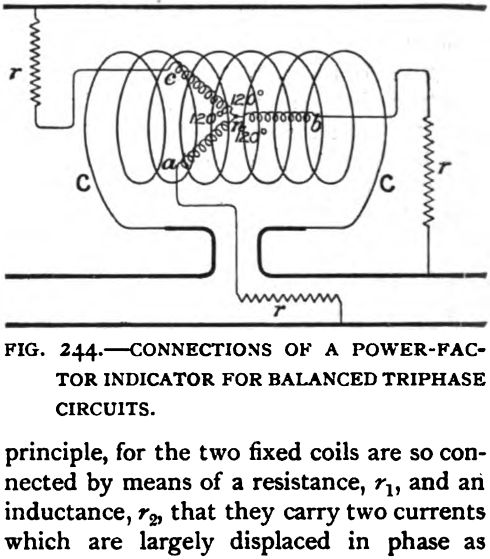


FIG. 244.—CONNECTIONS OF A POWER-FACTOR INDICATOR FOR BALANCED TRIPHASE CIRCUITS.

The calibration of these instruments is a matter of considerable difficulty, and is referred to in more detail at the close of the following chapter.

DR. SUMPNER'S PHASE METER.

In order to produce a phase meter whose indications should be more accurate, and which should be more sensitive, Dr. Sumpner devised an instrument which is, to all intents and purposes, a miniature polyphase motor. Its construction is indicated diagrammatically in Fig. 245. From this it will be seen that the main point of difference is in that the instrument has no rotating iron. There are two sets of iron stampings—an outer ring, A, and an inner cylinder, C—corresponding respectively with the stator and rotor of a motor, but what would be the rotor is here fixed, and in the annular air-gap between the two sets of stampings is a coil, N, pivoted so as to move freely in the gap, precisely like the coil of a D'Arsonval galvanometer or moving-coil ammeter. It is to this moving coil that the pointer, P, of the instrument is fixed, and the coil is a pressure coil—that is to say, the phase of its current is determined by the phase of the voltage. In order to prevent the variation in the space distribution of the flux density in the gap from affecting the coil as it moves from one slot to the next, the outer stampings are built up slightly staggered relatively to one another, so that the slots have an almost spiral form, and the moving coil therefore crosses the slot gradually. The instrument is most satisfactory in its behaviour, as well as being simple in principle and neat in construction.

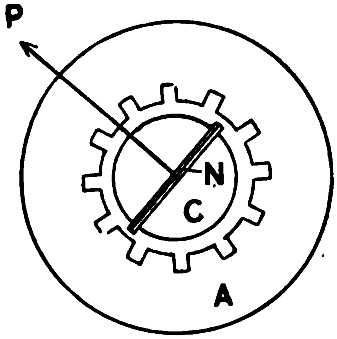


FIG. 245.—DIAGRAM OF SUMPNER'S PHASE METER. A, ANNALUS OF IRON; C, STATIONARY IRON CORE; N, MOVING COIL; P, POINTER.

IDLE CURRENT AMMETERS.

These instruments are essentially wattmeters, except that the pressure coil is so connected to the circuit that the current in it lags behind the pressure of the circuit by, as nearly as possible, 90°. If, then, the pressure and current of the main circuit are relatively displaced by the angle ϕ, the instrument will read $VC \sin \phi$, and its scale, as will be seen in Fig. 246, may either be calibrated in amperes or watts, and will then indicate what are called the "wattless amperes," viz. $C \sin \phi$, or the "idle watts," viz. $VC \sin \phi$. The real function of the

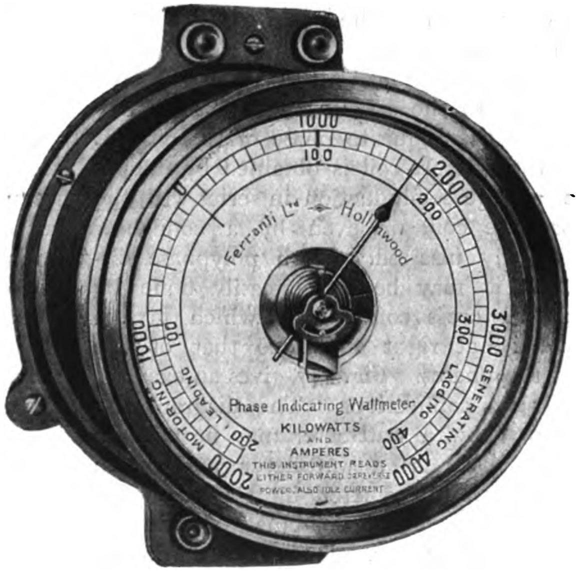


FIG. 246.—SCALE OF FERRANTI'S IDLE CURRENT AMMETER.

instruments is the same as that of power-factor indicators (phase meters), but is differently effected, since the condition of the circuit can only be determined by a comparison of the "idle current" with the whole current, or the "idle watts" with the apparent watts, or with the true watts. In the case of single phase instruments the requisite phase of the current in the pressure coil is obtained by the use of a large self-induction in series with the pressure coil, or even by a condenser similarly inserted. With polyphase circuits it may be more easily done by special cross connections, which give a voltage at right angles to that of one of the phases. Fig. 247 gives an example of such connections. The diagram also shows how a wattmeter may be used to serve both as a wattmeter and as an idle-current ammeter by the use of a reversing switch in combination with such cross connections. This idea is due to Mr. M. B. Field, and such instruments are made by Messrs. Ferranti & Co.

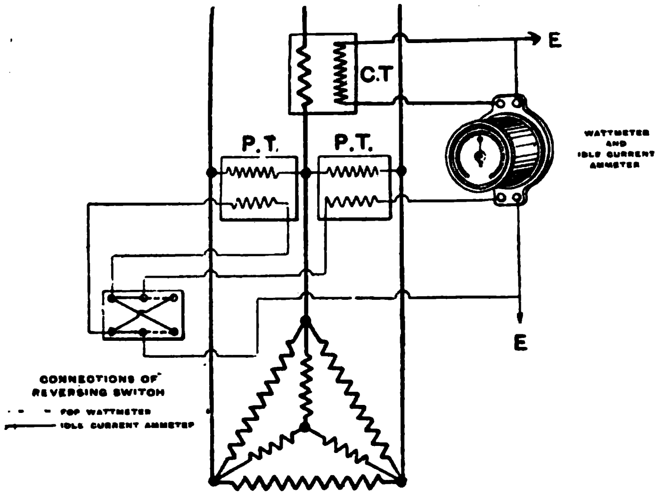

E
C.T
P.T.
P.T.
WATTMETER AND IDLE CURRENT AMMETER
E
CONNECTIONS OF REVERSING SWITCH
- - - FOR WATTMETER
——— IDLE CURRENT AMMETER

FIG. 247.—DIAGRAM SHOWING CONNECTIONS USED WITH WATTMETER, SO AS TO GIVE EITHER TRUE WATTS OR "IDLE WATTS."

FREQUENCY METERS.

It is often important to know what is the precise frequency of an alternating current circuit at some instant. It is not then sufficient to take the declared frequency as correct, since, owing to the exigences of central station working, variations in speed of the running machinery are inevitable, though they do not often amount to more than a few per cent. of the standard value. Instruments are now in use which indicate the frequency within about one-half per cent. Such instruments take the form of a series of tuned reeds, each capable of vibrating at some rate lying between the limits of variation to be observed. Impulses are given to all the reeds at once by the circuit, and resonance occurs in the case of that one whose natural period is of the same value as that of the impulses. In one type of instrument the reeds are all mounted on a rocking bar, to the foot of which is attached an electromagnetic device which rocks the bar with oscillations of the same frequency as that of the circuit. The consonant reed responds with vibrations of large amplitude, while the remainder are quiescent, or merely show "beats." The responding reed is thus easily discerned, and, as each is marked with the number of its natural periods per second, the frequency of the circuit is known.

In other well-known types, such as Johnson & Phillips's and Everett Edgcumbe's, the reeds are mounted on a frame and placed in a magnetic field produced by a coil connected to the circuit. The operation is otherwise the same as that of the type just described. Various

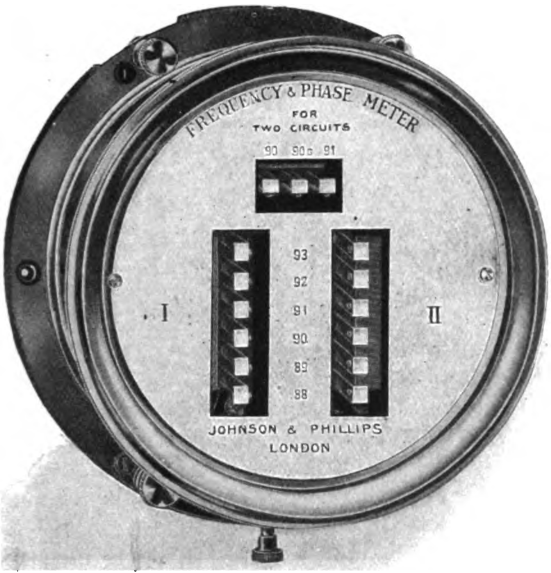


FIG. 248.—DIAL OF FREQUENCY METER ARRANGED AS SYNCHRONISER.

auxiliary devices are employed in conjunction with these instruments, and are indicated in the adjoining illustrations. A neat device is that employed in some instruments by Messrs. Johnson and Phillips, by which the range of the indications is doubled. The device consists in superposing a constant magnetic field at will upon the alternating one, the constant field being provided either from a permanent magnet or from a coil traversed by a continuous current. Again, an ingenious combination renders a frequency meter capable of acting as a synchroniser. This is shown in Figs. 248 and 249, from which it will be seen that three meters are combined in one case. That on the left is in circuit No. 1, and that on the right in the circuit of an incoming machine, and is No. 2. The third, the upper row, is permanently in circuit No. 1, and is of greater delicacy than the main No. 1 row, and is moreover provided with a second winding, which may be switched at will into circuit No. 2. If, now, the two main sets vibrate synchronously, but when No. 3 is switched into No. 2 (while still being in circuit No. 1) it stops, the two circuits are 180° apart, whereas, if the amplitude is greatly increased, the machines are in step. Very little practice enables true synchronism to be recognised with certainty. The connections are shown in Fig. 249, F_1 and F_2 being the magnets controlling the two main sets of reeds; F_3 the magnet having a double winding, one controlled by the switch, U; and M_2 the machine to be paralleled with M_1.

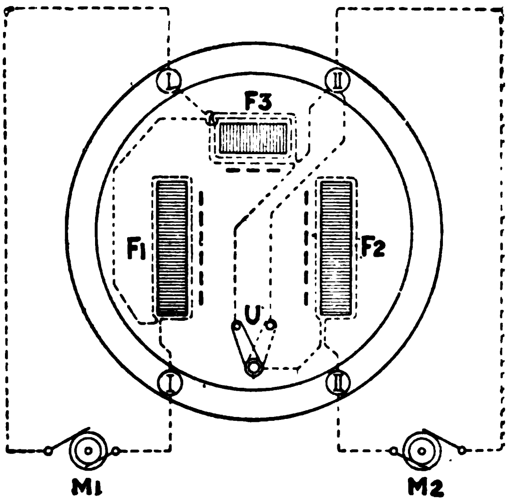


FIG. 249.—CIRCUITS OF FREQUENCY METER ARRANGED TO WORK AS SYNCHRONISER.

CHAPTER V.—METHODS OF TESTING.

ACCESSORY APPARATUS—KEYS, PLUGS AND STANDARDS—CALIBRATION OF GALVANOMETER—OF BALLISTIC GALVANOMETER—MEASUREMENT OF RESISTANCE—OF CAPACITY—OF SELF-INDUCTION—OF E.M.F.—OF CURRENT—CALIBRATION OF VOLTMETERS AND AMMETERS—BATTERY TESTING—WAVE TRACING—THE POTENTIOMETER.

BEFORE proceeding to describe the various methods used for the measurement of resistance, electromotive force, current, self-induction, and capacity, it will be necessary to briefly describe the various pieces of small apparatus required which are accessory to the galvanometer. Firstly, it is essential to have keys capable of making and breaking circuit, and of rapidly changing connections without having to disconnect any wires. The simplest of these is the "tapping key," which merely makes and breaks circuit, the ordinary form of which is shown in Fig. 250. This consists of two strips of springy brass, fixed one above the other. Circuit is made by bending the upper piece until it comes into contact with the lower. Both pieces are furnished with platinum contacts, and the upper has a fibre press-button attached to it. When, for very accurate work, extra high insulation is necessary, all the metal portions are mounted upon ebonite pillars, which are corrugated in order to make the surface leakage path longer. The pillars are attached to the ebonite base by means of screws, which must be short, as otherwise the effect of the ebonite is lost.

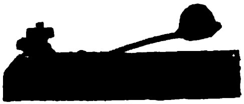


FIG. 250.—SIMPLE TAPPING KEY.

The above form of key is used when contact is to be made momentarily, or for a short time, but when it becomes necessary to maintain contact for a considerable time, it is inconvenient to have to hold the key depressed, and a plug key is often used instead. This type of key is shown in Fig. 251, from which it will be seen that it merely consists of two brass blocks mounted close to one another upon a wood or ebonite base. In the adjacent faces of the blocks are cut almost semicircular notches, into which a circular taper plug is inserted, thus completing the circuit between the two blocks. The taper given to the notches should correspond to that possessed by the plug, in order to give as large a surface of contact as possible, and, to ensure this, in the best makes the plug is carefully ground into its seating. Plug keys lend themselves well to adaptation as two, three or more way keys, all that is necessary being to surround a central brass block with a number of others each

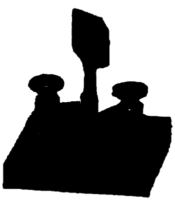


FIG. 251.—ONE-WAY PLUG.

furnished with a notch, the central block having as many notches as there are outside blocks. By inserting the plug in the different notches, any outside block can be connected to the central one. A good type of multiway plug switch is shown in Fig. 252.

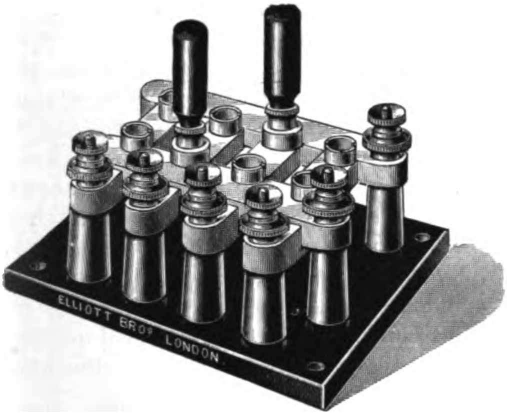


FIG. 252.—MULTIWAY PLUG KEY.

A piece of apparatus upon which the plug key is nearly always used is the resistance box. When measuring resistances, it is an absolute necessity to have a convenient and rapidly adjustable standard resistance, and this is usually made in the form shown in Fig. 253.

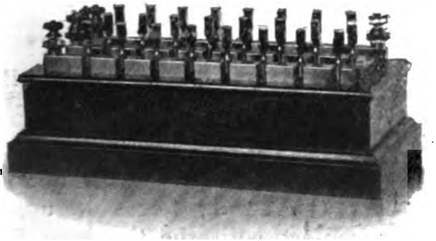


FIG. 253.—ORDINARY SERIES RESISTANCE BOX.

It consists of a box with an ebonite top, upon which are mounted close together a number of brass blocks, each one of which is capable of being connected to the one next to it on either side by means of a plug, as in the ordinary plug key, the top of each plug being provided with an ebonite head to insulate it from earth while it is being handled. Between each brass block and the next is connected a resistance, made of wire, wound non-inductively upon a bobbin (*see page* 198). The material of which the wire is made varies with the price of the box. In the more costly boxes, it is usually manganin, which has replaced to a large degree the platinum-silver formerly used; while in the cheaper forms German-silver or platinoid are used. When a plug is inserted between any two brass blocks, as in Fig. 254, the coil connected between them is short-circuited, and the plugs being ground in, as before mentioned, the resistance between the blocks is negligible.

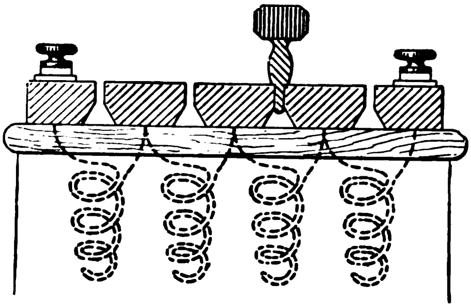


FIG. 254.—DIAGRAMS OF BLOCKS AND WINDINGS OF RESISTANCE BOX.

In some measurements, it is extremely useful to be able to make contact with any one of the brass blocks on the top of a resistance box, and this is done by means of a "travelling plug." Each block, in addition to the nearly semicircular notches provided at the edges, has a taper hole in the centre, into which a plug may be fitted. A "travelling" plug, such as is used for this purpose, is shown in Fig. 255. The top of the plug is provided with a terminal, to which a flexible wire is connected. By means of the ebonite disc, D, the plug can then be moved from point to point without being "earthed" by the operator's hand. For some work it is convenient to have a very much larger standard of resistance than that obtainable with the ordinary resistance box, and consequently resistances of one megohm are now obtainable. These are made in various ways, but if wire is used, they are very bulky and costly. An exceedingly portable and compact megohm, which is quite accurate enough for most practical purposes, can be made by making a wide streak with a soft graphite pencil on a piece of ground glass. A sufficient length of streak is taken to give a resistance of above one megohm, and after having been tested and adjusted, it is covered with another piece of glass for protection. Connection is provided by tinfoil clamped between the two glass slips on to the graphite, and by terminals connected to the tinfoil.

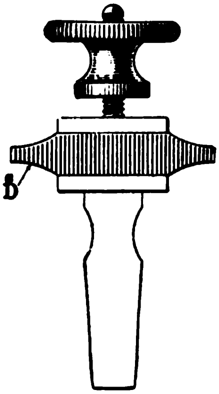


FIG. 255.—TRAVELLING PLUG.

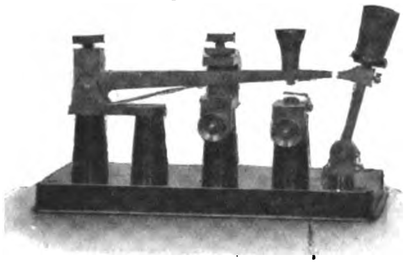


FIG. 256.—CABLE-TESTING KEY.

Keys of a more complicated nature than those first described are found in many cases to be necessary. Fig. 256 illustrates one of these, which is required in connection with the measurement of capacity, and is known as a "charge, insulate, and discharge" key. The middle movable tongue plays between upper and lower contact pieces, and in the normal position is held by a spring against the upper contact bar. On the end of the tongue are cut two steps, upon each of which the movable catch shown in the figure can rest. When the catch is resting on the top step, the tongue is held fully depressed, and touching the lower contact. When the catch is resting on the second step, the tongue is held midway between the contacts without touching either, and when the tongue is released altogether the spring forces it up, so making contact with the top bar. The specimen shown is also of high insulation, the conducting parts being heavily insulated on ebonite. Fig. 257 shows a similar type of discharge key devised by Mr. J. Rymer Jones. The action of this key will be readily understood from the accompanying illustration. The cable under test is connected to the principal terminal, and is "charged" or "discharged" as the levers are deflected to

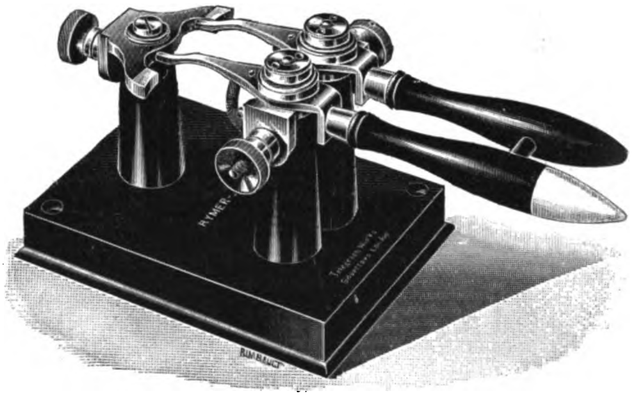


FIG. 257.—RYMER-JONES KEY.

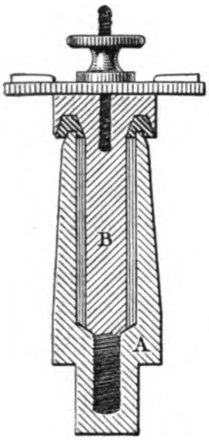


FIG. 258.—CABLE TERMINAL OF RYMER-JONES KEY.

one side or the other. The levers are made of brass with ebonite handles, and have their contact points tipped with platinum. The surfaces over which the levers rub are also platinum covered. A piece of ebonite projects laterally from one handle and prevents the battery and galvanometer terminals from being both connected to the cable at the same time. The principal terminal is left entirely free during the period of insulation, and is shown in Fig. 258 in vertical section. The inner portion, B, screws into the ebonite cup A, and by this method of construction the path over which any leakage occurs is increased from 2½ in. to nearly 6¾ in. without appreciable increase in height. The advantages derived from this construction are, firstly, that the cable end is disconnected from everything but its terminal during the "insulate" period, so that leakage is as small as possible, and, secondly, the inner ebonite pillar B can be unscrewed, and its surface cleaned with glasspaper when necessary without spoiling the appearance of the key. The handle of the galvanometer lever is tipped with ivory, so that it may be readily distinguished. Another most useful form of key is that invented by Morse, and known by his name. It was first used for signalling purposes, but proves very convenient for laboratory work as well, and is shown in Fig. 259. The rocking bar, *b* *b*′, which is pivoted between the supports, D D′, is made of metal, usually brass, and has a platinum contact on its lower surface at each end. Beneath both ends of the rocking bar are fixed brass strips, N and V, carrying platinum contacts, exactly opposite those mentioned above.

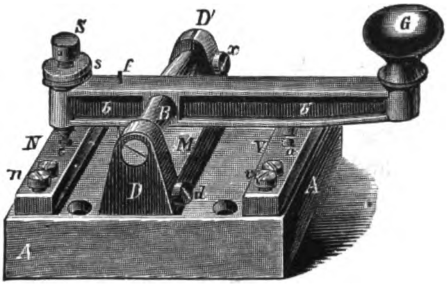


FIG. 259.—THE MORSE KEY.

One end of the bar is furnished with a knob, G, by which it can be depressed against the action of a spring, which normally tends to hold it in contact with the strip at the other end. It is thus seen that when the knob, G, is up, in the normal position, the brass piece, M, carrying the supports, D D′, is in connection through the pivot and platinum contact with the strip, N, while when the knob, G, is depressed, M is in connection with V. A form of key which takes the place of the Morse key when high insulation is desired is that consisting of a tongue moving between upper and lower contacts. It is known as a "charge and discharge" key, and is identical with the one described above except that the catch for holding the tongue is omitted.

A type of key which has an extended use is one used for reversing the direction of the current through a circuit. Fig. 260 shows a form of this key made for use on circuits where high insulation is required. There are two moving tongues, *c* and *d*, fitted with ebonite finger buttons upon which to press. Both these tongues move between upper and lower contacts, *a* and *b*. The source of supply is connected to the contacts, *a* and *b*, and the circuit through which it is desired to reverse the current to the moving tongues, *c* and *d*. Thus, when *c* is depressed, the current from the supply flows one way around the external circuit, and when *d* is depressed, the direction of flow is reversed. It is also fitted with spindles and cams, all of ebonite, which can be rotated so as to hold either key depressed. A form of reversing switch which is much used, especially where larger currents are to be handled, is shown in Fig. 261, and is known as Pohl's mercury commutator. In this case mercury cups are used as contacts, and bridged by stout copper wires. The terminals, A and B, are connected to the supply, and the connecting bridge K, which is made of insulating material, is rocked so that the curved pieces are connected through the mercury cups with either E and F or C and D. The external circuit is connected to either E and F or C and D. Then, if the bridge be in such a position that K is near the reader, A is connected to C, and B to D; if now the bridge be rocked to the position shown, A is connected through E to D, and B through F to C. There is another form of reversing switch which is used on induction coils, and also on old types of telegraph instruments, and this is shown in Fig. 262. It consists of a cylinder of insulating material, upon opposite diameters of which are fixed two brass segments. The axle upon which the cylinder is mounted is not continuous, and each segment is connected to one end of the axle, which is metallic. The bearings carrying the axle are also of metal, so that each bearing forms the connection with one of the segments. Two brushes press against the curved surface of the cylinder, and by rotating it either brush can be made to press against either segment. The supply is connected to the two brushes, and the external circuit to the two bearings, so that when brush A presses against segment A′, and brush B against segment B′, the current flows one way through the circuit, and when brush A touches segment B′, and brush B segment A′, the current is reversed.

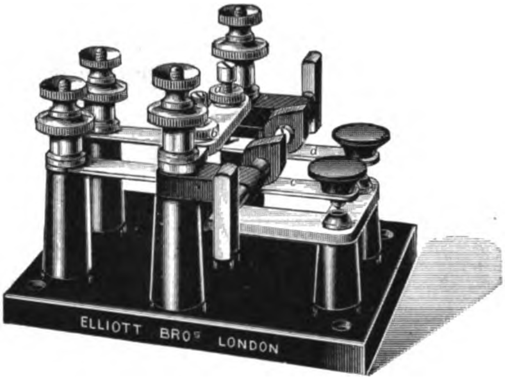


FIG. 260.—CHARGE AND DISCHARGE REVERSING KEY.

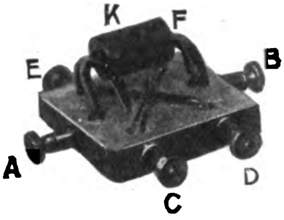


FIG. 261. — MERCURY-REVERSING SWITCH.

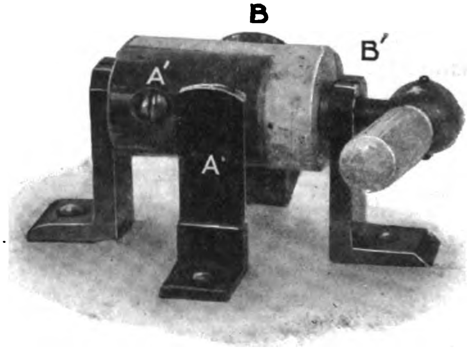


FIG. 262.—COMMUTATOR FOR REVERSING CURRENT.

In addition to the above pieces of apparatus, it is necessary to have also standards of capacity and self-induction. The standard of capacity takes the form of a number of sheets of tinfoil separated by either thin sheets of mica, or by paraffined paper. Alternate sheets are brought out to the same terminal, and adjacent sheets, therefore, to opposite terminals. The connections are brought out to brass blocks on the top of the box, which can be connected by means of a plug, so as to short circuit the condenser.

The construction of these condensers is exceedingly simple. A number of sheets of thin, tough paper, absolutely free from pin holes are obtained, and also a number of sheets of tinfoil, which should not be at all crumpled. The tinfoil sheets are cut up into rectangles of a convenient size, with a projecting lug, either at one corner, or in the centre.

A vessel, preferably water jacketed, contains molten paraffin wax, which must be kept thoroughly hot* during the operations. The paper sheets should be cut to such a size that they overlap the tinfoil sheets by from a half an inch to an inch all round. A piece of wood, boiled in the wax, or a piece of ebonite, is taken, and a sheet of paper which has been dipped in the wax is laid on it while hot. Upon this is placed a sheet of tinfoil, with its lug projecting, say, to the left. Then another sheet of hot waxed paper and another sheet of tinfoil, this time with its lug to the right. These operations are repeated, the tinfoil lugs projecting alternately right and left, until sufficient sheets have been used to give the required capacity. A second piece of wood or vulcanite is then put on top, and the whole tied together and heated in paraffin wax for some time. While quite hot, it is then put in a press, and considerable force exerted, squeezing out all superflous wax, and getting the tinfoil sheets as close together as possible; it is allowed to remain in the press until cold. All that remains to be done is to clean the tinfoil lugs and solder them to terminals when the condenser is ready for use.

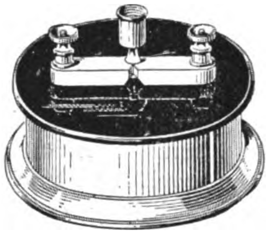


FIG. 263. — CONDENSER WITH SHORT-CIRCUITING PLUG.

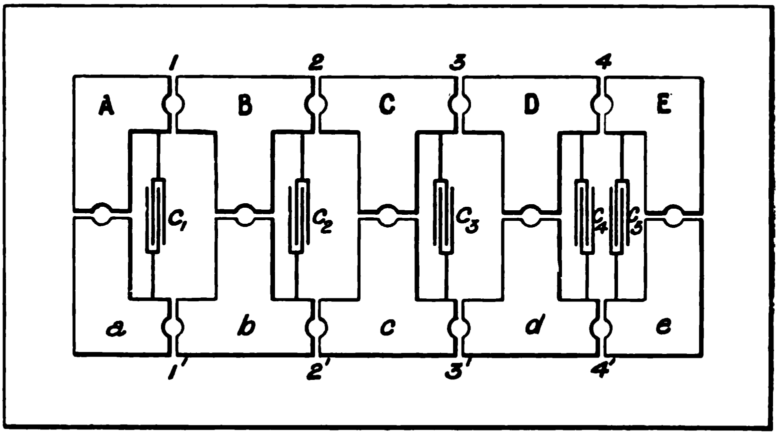


FIG. 264.—CONNECTIONS OF CONDENSER BOX.

The most usual size for standard condensers is one-third of a microfarad, and one of this size is shown in Fig. 263. They are also made up in the same forms as resistance boxes, with the exception that to add the capacities of two condensers they must be put in parallel, while to add two resistances they must be put in series, this fact of course, making the arrangement of the plugging contacts somewhat different. Fig. 264 shows the actual connections of one of these condenser boxes, by means of which the condensers can be put either in parallel or in series.

---

* The wax must on no account be heated above the temperature of boiling water at any time during this or subsequent operations. Wax that has at any time been overheated should not be used for condensers.

By putting in plugs 1, 2, 3, 4 and 1′, 2′, 3′, 4′, and using terminals, A, *a*, the condensers are all in parallel. To put them in series, plugs 1′, 2, 3′, and 4 are inserted, and terminal A and *e* used. The box is also provided with holes, by inserting plugs in which any condenser can be short circuited.

The standard of self-induction is sometimes made up also in the plug box form, and usually contains inductances of 10, 20, 30, and 40 millihenrys. When much finer adjustment is required another type is used, consisting of two coils wound on frames which are portions of spheres, one of them being fixed, and the other revolving inside it about a vertical axis. The coils are connected in series, and when one lies directly over the other, with the current circulating in the same direction, the self-induction is a maximum, but is a minimum and nearly zero when the current circulates in opposite directions. The axle attached to the moving coil has a pointer fixed to it which moves over a scale graduated either in degrees, or directly in millihenrys, the usual range being from 0.004 to 0.04 henry. Fig. 265 shows a box form of self-induction, and Fig. 266 one of the variable type.

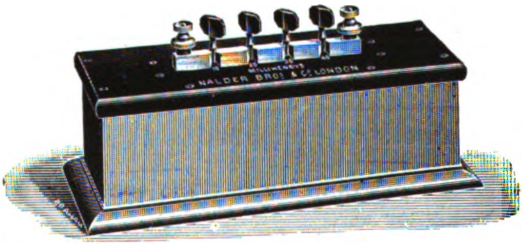


FIG. 265.—SELF-INDUCTION BOX.

CALIBRATION OF REFLECTING GALVANOMETER

Having briefly described the most common varieties of the chief forms of accessory apparatus, we must now proceed to consider how the readings of the galvanometer are to be given a definite meaning in current, quantity, or E.M.F., or in other words, how the galvanometer is to be calibrated. We will first show how this can be done for an ordinary sensitive reflecting galvanometer, such as a D'Arsonval.

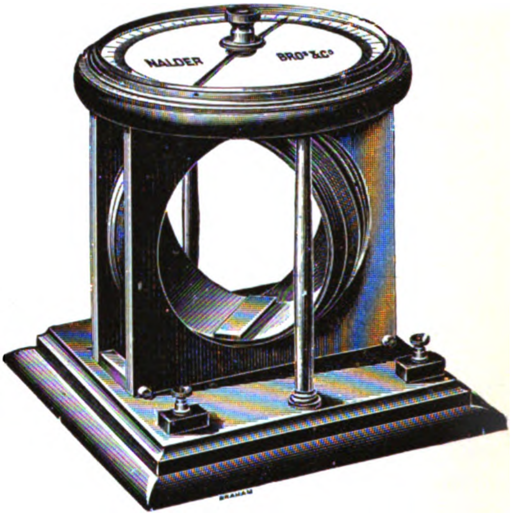


FIG. 266.—VARIABLE STANDARD OF SELF-INDUCTION.

It is first necessary to measure the resistance, *r*, of the galvanometer, G. This can best be done on a Wheatstone bridge, care being taken to either clamp or remove the moving part of the galvanometer, in order that the suspension may not be damaged by the forces due to the comparatively large testing current employed; the temperature at which the test is made should also be noted. The diagram of connections for calibration is shown in Fig. 267. C is a single cell of a storage battery, which is much preferable to a primary battery, on account of its practically constant E.M.F. This cell is connected through the low-resistance galvanometer, A, to the resistance, B E, which should not be less than 10,000 ohms. The galvanometer to be calibrated, G, is connected through the reversing switch, K, and the variable resistance, R, across a part of the resistance, B E, and the galvanometer, A. Thus the circuit of the galvanometer, G, only has a fraction of the total E.M.F. of the cell across it. The deflection of galvanometer, A, must be kept constant during the experiment by slightly altering the resistance between F and E. The resistance, F B, must also be kept constant. Now, as the current along B E is unvarying, and the resistance, B F, is constant, it follows that the E.M.F. across B F must be constant, and therefore the current through the galvanometer, G, is inversely proportional to the sum of the resistances of G and R, that is to $\frac{1}{r+R}$ where r is the resistance of the galvanometer. Thus, starting with R fairly large, and the deflection on G therefore fairly small, take a reading of the deflection and the value of R.

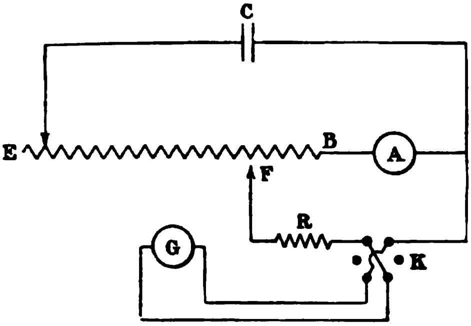


FIG. 267.—CIRCUIT DIAGRAM FOR GALVANOMETER CALIBRATION.

With the same value of R, take the deflection on both sides of zero, reversing the current by means of the key, K. Next slightly decrease R, and so increase the deflection, again reading both sides of zero. Proceed thus until a series of readings have been obtained. Now plot the deflections to one side of zero against the reciprocal of the sum of the resistances of r and R, and plot a similar curve for the deflections on the other side of zero. If it be wished to calibrate the galvanometer directly in current, the voltage across B F may be measured by any of the methods to be described later, and by dividing this voltage by the sum of the resistances of r and R, the current can be ascertained. Of course, both the resistances, r and R, must be corrected to the temperature at which the experiment is made.

The distance of the scale from the mirror, the length of a scale division, and the period of vibration should also be kept for reference.

Another method by which the current for any one value of $\frac{1}{R+r}$ can be found is by the use of the iodine voltameter. This voltameter has been constructed especially for measuring small currents, and is due to Mr. Herroun. It consists of a deep beaker, at the bottom of which is placed a platinum anode, connection being made to this by a platinum wire sealed into a glass tube. The cathode consists of a zinc rod, one end of which is wrapped in a piece of filter paper, to keep particles of metallic zinc from falling to the bottom of the beaker. This rod only dips a few centimetres into the solution. The electrolyte consists of a 10–15 per cent. solution of neutral zinc iodide, which should, when not in use, be kept in a dark place in contact with a little pure zinc, or it will decompose.

When a current is sent through the voltameter, iodine is set free at the platinum anode, but owing to its density remains at the bottom of the beaker. The current density at the cathode should not exceed 1 ampere per 31 square inches, as otherwise insoluble periodate is liable to be formed.

As soon as electrolysis is complete, the zinc cathode is removed, and the solution well shaken up to dissolve the iodine, the amount of which liberated is 0·001314 gramme per coulomb. The amount liberated is determined by titration with pure sodium thiosulphate. A convenient strength for the sodium thiosulphate solution is 12·845 grammes to 1,000 cubic cms. of distilled water, 1 cubic cm. of this being equivalent to 0·00657 gramme of iodine, that is, to 5 coulombs of electricity. The solution of sodium thiosulphate is placed in a burette, and the beaker containing the brown solution of iodine placed under it upon a white ground. The thiosulphate is now run into the iodine solution until nearly all colour has disappeared, when it is added drop by drop until every trace of colour has gone. If preferred, near the end of the titration, a little starch solution may be added, when the blue colour due to the free iodine may be made to disappear by the addition of the thiosulphate.

In either case, the number of cubic cms. of thiosulphate solution used multiplied by 5 gives the number of coulombs of electricity which have passed, and this number divided by the time of electrolysis in seconds, gives the average current in amperes.

BALLISTIC GALVANOMETERS.

We have seen that the first swing may be taken as a measure of the energy imparted to the suspended system. Now this energy is the sum of all the products of current and time, and hence what is actually measured is the quantity of electricity. For this reason ballistic galvanometers are always employed for the measurement of capacity, the condenser to be tested being allowed to discharge itself through a ballistic galvanometer, the first swing so produced being compared with that produced by a standard condenser charged to the same voltage, or to some known multiple or sub-multiple of it. It is fairly common practice to employ shunts to ballistic galvanometers. For closely accurate work this practice must be avoided since the damping action of the shunt depends upon its resistance. This is clearly so, for the magnitude of the (damping) currents induced by the swinging magnets must depend on the resistance of their path, which is partly through the shunt. More important than such variation in the damping is the fact that the currents to be measured are transient or impulsive, and hence (*see* Sec. VI., Chap. I.) set up self-inductive actions. Now the function of a shunt is to divide the current of the circuit between the galvanometer and the shunt in a known proportion, and for this the relative resistances of shunt and galvanometer are relied upon. In a circuit carrying a varying current, however, the effect of self induction may be greatly more important than that of resistance, and it is quite out of the question to devise shunts such that both their resistance and self induction shall have the required known ratio to those of the galvanometer. Where, therefore, the galvanometer deflection has to be reduced, it is far preferable to do so by reducing the E.M.F. in a known proportion rather than by shunting the galvanometer. Fortunately this may be very easily done in a way that is not always applicable to other tests. It is, however, invariably applicable to condenser tests, since, whatever the size of the condenser, when it is fully charged the current into it is zero. In other words, since no current is being taken at the end of the charging operation, any device for sub-dividing the E.M.F. may be employed regardless of the resistance which it introduces.

Ballistic galvanometers are also largely used for the measurement of magnetic fields. For this purpose the field to be measured is embraced by a coil of a known number of turns, and is then either suddenly withdrawn or reversed. In either case the result is to produce the cutting of the whole of the lines of the field once or twice by the whole of the turns of the coil, this latter number being accurately known. The E.M.F. produced is $\frac{dN}{dt} \times S$, and the current at any particular instant is this E.M.F. divided by the resistance or the circuit, which consists of the coil in question and the galvanometer only. Now, as we have seen, the first swing depends upon the whole quantity of electricity which passes through the galvanometer, and is hence equal to

$$\int_0^t \frac{dN}{dt} \times \frac{S}{R} \times t, \text{ or,* } \frac{N}{t} \times t \frac{S}{R} = \frac{NS}{R}$$

A brief inspection of this expression shows that if the galvanometer be truly ballistic, and provided the field is never wiped out or reversed so slowly as to destroy the ballistic action, the first swing will be proportional to the product of turns and field only, and is quite independent of the rate at which the cutting takes place. This gives us an excellent means of comparing magnetic fields, the only drawback to the method being that common to all ballistic work, of being exceedingly tedious, by reason of the undamped swinging of the needle.

HINTS ON USE OF BALLISTIC GALVANOMETERS.

It will be well here to give a few hints as to the use of ballistic galvanometers. The undamped swinging of the needle, which is such a cause of tedium and delay, can be very much reduced in the case of a moving coil instrument by the employment of a short-circuit plug. The terminals of the plug are connected directly to those of the instrument, and as soon as a reading has been taken, short-circuit is made by the plug (or a key may be used), and the instrument very rapidly comes to rest. The cause of this is that the coil, as it swings between the poles of the permanent magnet, generates currents like a small oscillating dynamo, the tendency of the currents being always to retard the motion. (*See* page 229, Lenz's Law.) A plug is, on the whole, preferable to a key, unless a Morse key be used, since the galvanometer may be left thoroughly protected against misuse, provided the simple precaution of leaving the plug in is taken. On the other hand, the Morse key would have to be held down all the time the reading is being taken. In the case of the Thompson four-coil ballistic galvanometer, damping is best effected by means of a small auxiliary coil external to the galvanometer, and preferably without an iron core. The coil may be mounted on any convenient stand and connected in circuit with one or two Leclanche cells and a key. By tapping the key at suitable instants, the swinging of the needle may be stopped rapidly.

Firstly, the logarithmic decrement should be carefully measured (*see* page 253), and the eye accustomed to the period of swing. The decrement should be small if the instrument is to be accurate, and by accustoming the eye to the period, great accuracy may be secured in noting the precise limit of the first swing. If possible, a preliminary observation should be made, so that when the accurate observation is to be made the eye may be directed approximately to that point in the scale which will be reached by the spot. By this means the position of the line can easily be read with great exactitude, provided the period is long; that is, provided the instrument swings very slowly, as all good ballistic instruments should. In the second place, very great care should be taken that the needle has come to rest completely before a reading is taken. In cases where great accuracy is required there must be no limit to the observer's patience in attaining this end. Careful damping and short-circuiting must be resorted to to ensure complete rest, so that when the impulse is given to the needle the first swing is in no way affected by the needle having motion in one direction or the other, which would add to or reduce the magnitude of the reading. Thirdly, it should be borne in mind that the circuit through which the impulse is given to the needle itself provides some damping action similar, though very much less in degree, to that of the short-circuiting plug, and hence the logarithmic decrement should be measured with the galvanometer terminals connected to the circuit from which, in working, it will take its impulses. So far we have spoken of the observations merely of the magnitude of the first swing, but in point of fact, however, that which is proportional to the energy of the impulse is the sine of half the angle of the first swing. In almost all cases ballistic readings are taken by means of reflecting galvanometers, and with these instruments the distance of the scale from the mirror is very considerable, and the length of the scale is small in comparison with that distance. Further, the angular movement of the beam of light is twice that of the mirror, hence the angular motion of the mirror is, as a rule, extremely small. If the scale be straight, as it commonly is, it forms a tangent to the circle whose radius is the distance from mirror to scale, and the deflections along the scale are really measures of the tangents of the angles of deflection. Now for such small angles, both sines and tangents are very nearly proportional to the angles themselves, so that in the first place it is of little import whether we read sines or tangents, and in the second place the sine of half the angle of deflection is practically the same as half the sine of the angle of deflection. Although this is true, it becomes in some cases desirable to resort to every possible means of obtaining accuracy, and if every other means has been exhausted, attention may then be turned to the true law of the galvanometer and sines of half the angles be taken. This may be done in two ways: either one may take the readings as tangents and convert from them, a somewhat inaccurate method, or the scale may be made circular to the radius of the distance of the mirror from the scale, and the sine of one quarter of the angle indicated by the movement of the spot taken as proportional to the energy delivered to the needle. One quarter of this angle is taken since the spot moves through twice the angle moved through by the mirror, and sine of one half of that angle is what is wanted.

---

* Assuming, as may be done with sufficient accuracy for the majority of cases, that the rate of change $\frac{dN}{dt}$ is constant; failing this, $\frac{N}{t}$ is only an average, of course.

Another point demanding care in the use of ballistic galvanometers, if of the Thompson type, is the constancy of the controlling magnetic field. If during the series of observations it be noticed that the zero of the instrument frequently changes, the strength of the controlling field should be suspected as well as its direction, and indeed, whenever Thompson instruments are used ballistically the constant should be continually checked by taking throws with an earth coil, or preferably with a standard solenoid. Where sufficient sensitiveness can be attained, it is usually preferable for the above reasons, to employ ballistic galvanometers of the D'Arsonval type. Very great care must, however, be employed in selecting the materials of which the coils are made, in order to avoid the inclusion of magnetic material in them.

Even so innocent a material as copper has been found to be quite appreciably magnetic owing, probably, to minute particles of steel from the dies through which the wire was drawn. Such difficulties can, however be overcome, and have been overcome, by good makers. The D'Arsonval type of galvanometer demands very careful calibration, since the ordinary ballistic formula does not necessarily apply to it, in consequence of the control being exerted by the suspension instead of by a uniform magnetic field.

CORRECTION OF DEFLECTION.

On page 253 it was shown how the logarithmic curve is plotted, and it is of course evident that however small the damping effect due to the friction and eddy currents may be, the magnitude of the first swing of the needle would have been greater if this damping effect had been entirely absent. Further the damping effect is variable, since it varies with the resistance of the circuit to which the galvanometer is connected, and hence with every change of search coil. It is therefore necessary for accurate work to determine the correction under the working conditions of the circuit. It is found the amplitudes of the deflections decrease in a geometrical progression, a_1, a_2, a_3, a_4, that is,

$$\frac{a_1}{a_2} = \frac{a_3}{a_4} = \frac{a_5}{a_6} = C$$

where C is a constant. The logarithm of C to the base ϵ is called the logarithmic decrement, and is usually denoted by λ. Calling a_m the amplitude of the mth swing, and a_n the amplitude of the nth swing, it can be shown that

$$\lambda = \log_\epsilon C = \frac{1}{n-m} (\log_\epsilon a_m - \log_\epsilon a_n)$$

Let a be the observed amplitude of the first swing, and A the amplitude it would have had if there had been no damping, then it can be shown that

$$A = a \left(1 + \frac{\lambda}{2}\right)$$

CALIBRATION: EARTH COIL METHOD.

The simplest method of calibrating a galvanometer of this type is by means of an earth coil. This consists of a carefully constructed coil of wire of a known, and preferably large, number of turns, and of known, and also large, area. To obtain the true mean diameter of this coil, the diameter should be carefully measured over each successive layer while the coil is being wound, and the figures recorded. The coil is connected to the terminals of the galvanometer and placed with its axis vertical. When the galvanometer spot is at rest, the earth coil is turned through 180°, so that it is lying on its other face, with its axis again vertical, having twice cut the vertical component of the earth's magnetic field. The deflection of the spot is noted. The calculation is then to be made as follows:

Let A be the mean area of the earth coil in square centimetres,
v be the vertical component of the earth's field,
s be the number of turns on the earth coil,
then the total cutting of lines, M, is given by $M = 2 A v s$.

Now if R be the sum of the resistances of the galvanometer and earth coil, and Q the quantity of electricity,

$$Q = \frac{M}{10^8 R} = 2 \frac{A v s}{10^8 R}$$

The value of the deflection for the quantity Q is now known, and this deflection can be corrected by the method explained above.

STANDARD SOLENOID.

Where either the constancy of the earth's field cannot be relied upon, or where a variable field of known strength is desired for the calibration of a D'Arsonval type of ballistic galvanometer, a known field may be artificially produced by means of a standard solenoid. This consists, as its name implies, simply of a solenoid which has been carefully constructed and the dimensions of which are very accurately known. The current passing through it must also be very carefully measured at the time of using. The field so produced may then be employed to generate currents in a search coil wound outside the solenoid and connected to the galvanometer to be calibrated. The solenoid should be of a length from ten to fifteen times its mean radius, the lower limit being the shortest that should ever be employed. It is, of course, permissible, although inconvenient, to employ a length greater than fifteen times the radius. The solenoid should be wound on a tube of non-magnetic material, and preferably a material which is a non-conductor. If it can be protected from rough usage, glass forms an excellent tube. Failing this, brass or copper may be employed, but if a metal is used it must be split longitudinally, to prevent the generation in it of secondary currents when the current in the winding is stopped, started, or reversed. Ebonite or vulcanised fibre may be used, but both of these are somewhat liable to deformation, and ebonite in particular is very liable to contain magnetic material over and above any free sulphur. Where possible the author greatly prefers glass to any other material, since it possesses no drawbacks other than demanding considerable care during the construction and careful use subsequently. The dimensions that must be known when great accuracy is required are the outside diameter of the tube, the diameter over each layer of winding if more than one layer be used, the number of turns in each layer, and the total length of each layer. No pains should be spared to secure accuracy in these measurements, and the whole solenoid should be well mounted on a substantial base, so that it may be used in a truly horizontal position ; that is, with its axis horizontal. It is well to have a line carefully scribed on the base of the instrument parallel to the axis of the coil to serve as a reference when it is desired to place the coil with its axis lying truly at right angles to the magnetic meridian. Fig. 268 shows a standard solenoid. The ends of the winding should be carefully twisted together, and for this reason it is desirable to put an even number of layers of winding, so that the ends of wire come out together, thus enabling them to be at once twisted together to eliminate any slight magnetic effect due to current in them. The search coil to be used with the standard solenoid is more or less unimportant ; so long as it lies fairly closely over the solenoid and is not spread over too great a length, the results may be relied upon as being accurate. The length occupied by the search coil should not exceed one quarter of the length of the solenoid, and, of course, the number of turns in the search coil should be accurately known.

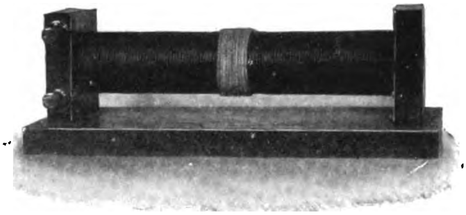


FIG. 268.—STANDARD SOLENOID AND SEARCH COIL.

Calculations may then be made thus: Let S be the number of turns of wire in the solenoid, s be the number of turns of wire in the search coil, r be the mean radius of the solenoid in centimetres, l be the length of the solenoid in centimetres, C be the current in the solenoid. The field strength in the centre of the solenoid is

$$H = \frac{4\pi}{10} \frac{CS}{l} \left(1 - \frac{1}{2} \frac{r}{l}\right)$$

The total flux N is this strength multiplied by the mean area A, in square centimetres

$$N = \frac{4\pi}{10 l} CSAp$$

Where p is the correction used above for end effect

$$p = \left(1 - \frac{1}{2} \frac{r}{l}\right)$$

If the current be suddenly stopped, the total amount of cutting of lines m by the search coil is

$$m = Ns = \frac{4\pi}{10 l} CSs\ Ap$$

The mean E.M.F. due to this is

$$\frac{m}{10^8 t}$$

Where t is the duration of the operation in seconds, the total quantity Q is $c \times t$ or

$$Q = \frac{m}{10^8 R t} \times t = \frac{m}{R} \times 10^{-8}$$
$$= \frac{4\pi}{10^9 l R} CSs\ Ap$$

If the main current is *reversed*, Q has twice the above value.

By taking observations of the throws of the galvanometer when currents of differing strength are employed in the solenoid, results may be obtained from which may be plotted a calibration curve connecting the throw of the galvanometer with the quantity that has passed. The curve may also with advantage be marked in terms of m and of s, the value of R being clearly stated as well. The working details of scale distance, periodic time, etc., should be carefully noted on the curve. This method of calibration is particularly suited to instruments of the D'Arsonval type, but is applicable to either.

MEASUREMENT OF RESISTANCE.

Probably the most common measurement which occurs in electrical work is that of resistance, and the method employed in its measurement depends on whether the resistance be high, as insulation resistance; medium, as that of the shunt winding of a dynamo; or low, as that of a copper bar. For the measurement of high resistance two methods are commonly employed. One of these is known as the ohmmeter and generator method, and is used for measuring the insulation resistance of electrical apparatus, light installations, etc. The second, known as the "loss of charge" method, is used for the measurement of even higher resistances, such as that of a short length of cable, or the dielectric resistance of a condenser. The "ohmmeter and generator" method lends itself to rapid and easy measurement of insulation resistance, and is in consequence much used for commercial testing.

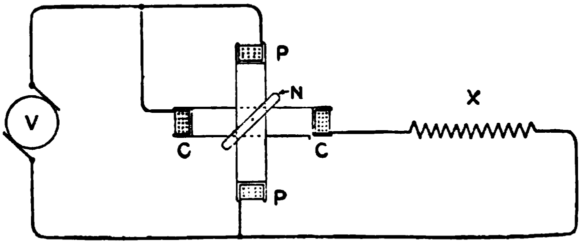


FIG. 269.—PRINCIPLE OF OHMMETER. V, SOURCE OF PRESSURE; C C, CURRENT COIL IN SERIES WITH EXTERNAL RESISTANCE DIRECTLY CONNECTED TO PRESSURE; P P, PRESSURE; N, MAGNETISED NEEDLE; X, RESISTANCE UNDER TEST.

One form of the apparatus consists of a magneto generator connected to a differential galvanometer. The generator has permanent magnets, a drum or **H** armature, and a commutating device, so that the current is a continuous one. The galvanometer or ohmmeter has the usual two coils—one the pressure coil, connected through a resistance across the terminals of the generator, the other the current coil, having one end connected to the generator, and the second brought out to a terminal on the case. A wire is brought from the other side of the generator to another terminal on the case, and the resistance to be measured is connected up between these two terminals. Fig. 269, showing a diagram of connections, needs no explanation.

A D'Arsonval form of this instrument has been put on the market by Messrs. Evershed and Vignoles, who call it the "megger." Fig. 270 gives a very good idea of the construction of one of these instruments. Two permanent magnets form the magnetic circuit, which provides the fields for both generator and ohmmeter.

The two coils of the ohmmeter are on a common axle, and are at a fixed angle from one another, the angle being such that, when any movement takes place, the current coil cuts a constant field, whereas the pressure coil, as it moves round, cuts a stronger and stronger field.

When the armature is turned by means of the geared handle, current is generated, and passes by way of the commutator, B, Fig. 271, to the terminals, T, where it divides, one part going through E to earth. If the insulation of the cable is perfect no current flows, but if the insulation is poor, current passes through it to the copper core, thence to L, and through R to terminal 2, through the current coil to terminal 1, and then back to the negative brush of the armature. When the current divides at E, the other part passes by way of Q to terminal 3, thence through the pressure coil to terminal 1, and so back to the negative brush.

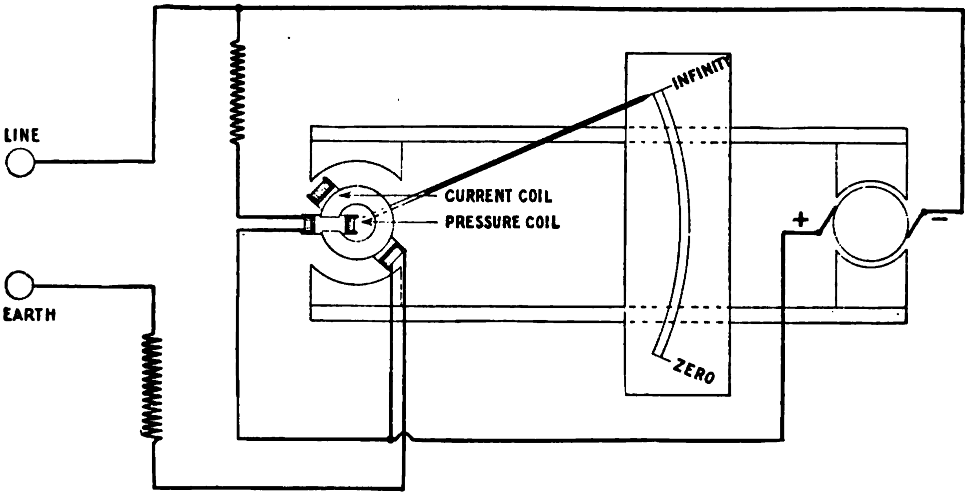


FIG. 270.—PRINCIPLE OF EVERSHED AND VIGNOLE'S "MEGGER."

If the insulation of the cable were perfect, no current would take the first path, and, consequently, only the pressure coil would be energised. The winding of this coil is so arranged that the passage of a current through it tends to produce an anti-clockwise rotation, and so keeps the system at rest against the stop. The

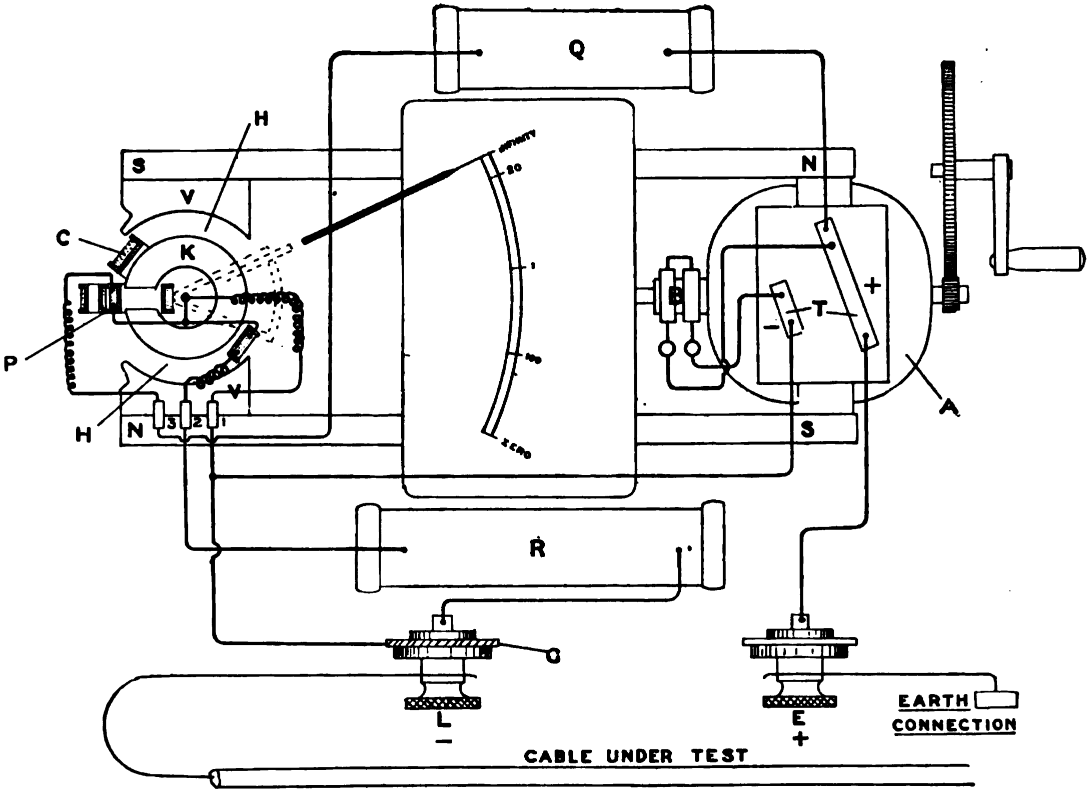


FIG. 271.—THE OPERATION OF EVERSHED AND VIGNOLE'S COMBINED OHMMETER-GENERATOR.

REFERENCES.

A, GENERATOR ARMATURE.
B, GENERATOR COMMUTATOR.
C, OHMMETER CURRENT COIL.
E, EARTH TERMINAL.
G, GUARD PLATE.
H H, ANNULAR AIR GAPS.
K, IRON CORE.
L, LINE TERMINAL.
N S, FIELD MAGNETS.
P, PRESSURE COILS.
Q, RESISTANCE IN SERIES WITH PRESSURE COILS.
R, RESISTANCE IN SERIES WITH CURRENT COILS.
T, TERMINALS OF GENERATOR.
V V, POLE PIECES OF OHMMETER.
1, COMMON TERMINAL OF CURRENT AND PRESSURE COILS.
2, TERMINAL OF CURRENT COIL.
3, TERMINAL OF PRESSURE COIL.

lower the resistance of the insulation under test, the greater will the current through it be, and this, passing through the current coil, tends to produce clockwise rotation. If the resistance were gradually decreased, the system would move in a clockwise direction, and in so doing would bring the pressure coil into a stronger field, and thus increase the controlling force, until the two opposing forces being equal, the system would come to rest.

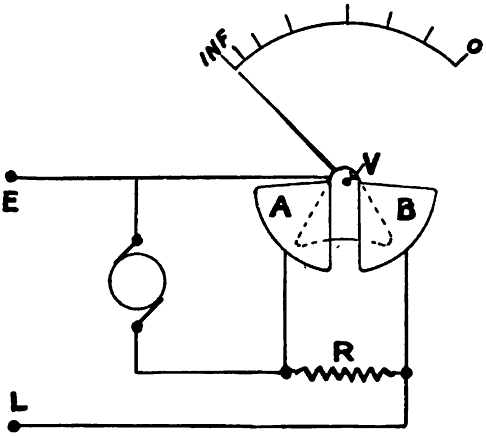


FIG. 272.—CONNECTIONS OF NALDER BROTHERS AND THOMPSON'S "OHMER."

The principle of Price's guard wire has been applied to the instrument, any leakage across the surfaces of insulation of the instrument itself being shunted past the current coil, so that it does not pass through either of the coils, and hence does not vitiate the measurement of the insulation under test. This shunt is shown leading from G to the negative side of the coils, Fig. 271.

The advantages of this instrument are that it is small and easily handled; has a wider range than the old type; is dead beat; and is not affected by any ordinary external fields, owing to its own powerful permanent magnets.

Another recent form of combined ohmmeter and generator is made by Messrs. Nalder Brothers and Thompson, who call it the "ohmer." The generator is of the permanent magnet variety, the armature being driven by a "free-wheel" gear, which protects the toothed gearing from injury when the handle is suddenly stopped. By reason of a special design of commutator, carbon brushes in spring brush-holders are used, and are found satisfactory.

The ohmmeter and generator are mounted on a common support, so that the slight vibration of the generator may be transmitted to the ohmmeter, and eliminate errors due to friction in the ohmmeter pivots. This applies equally to the instrument just described. The ohmmeter is an electrostatic instrument, and is therefore unaffected by external magnetic fields, and may be safely used in close proximity to dynamos at work. It has four sets of fixed vanes, with thirteen in each set, and the needle is attached to twelve double vanes of mica covered with aluminium leaf. The framework, except the magnetic circuit of the generator, is of aluminium.

Fig. 272 is a diagram of the connections of the instrument, but shows only half the vane structure, viz. two sets of fixed vanes and one side of the movable set. The generator has one of its terminals attached directly to one quadrant, A, of the ohmmeter, and the same terminal connected through a resistance, R, to the other quadrant, B, and thence to the line under test. The second terminal of the generator is connected to the vane, V, which is earthed. Opposite pairs of the fixed quadrants are connected together. When the insulation between earth and line is perfect, there is no current through R, A and B are therefore at the same potential, and V takes up the position shown. If the insulation is not perfect, a current flows between E and L, occasioning a potential difference between the ends of R, and therefore between A and B, which causes V to take up a new position, which will be shown by the pointer on the scale. The vane, V, is shaped approximately as shown so that it may be in stable equilibrium in all positions.

The "loss of charge" method is more of a laboratory one, although it is commercially used for testing cable insulation. The principle upon which the method is based is the following:—

If a condenser receives a charge, the potential of one plate rises above that of the other, and if the insulation of the condenser were perfect, it would remain charged for an indefinitely long time. As, however, the charge slowly leaks, the potential difference falls, and from the fall of potential in a given time and the capacity of the condenser, the quantity of electricity lost may be calculated, and from this the insulation resistance, as follows:

Let r = the insulation resistance in ohms, E_1 and E_2 = the potential difference between the plates at the beginning and end of the time t, K = the capacity of the condenser in farads, q = the instantaneous value of the quantity of electricity in the condenser, e = the instantaneous value of the potential,

$$q = \text{K}\, e \text{ and } dq = \text{K}\, de$$

$$\text{but current} = \frac{dq}{dt} = \frac{e}{r}$$

$$\therefore \text{K}\frac{de}{dt} = \frac{e}{r} \text{ and } \frac{dt}{\text{K}r} = \frac{de}{e}$$

Integrating we have

$$\frac{t}{\text{K}r} = \log_e \frac{\text{E}_1}{\text{E}_2}$$

$$\therefore r = \frac{t}{\text{K} \log_e \frac{\text{E}_1}{\text{E}_2}}$$

If preferred, the quantity of electricity in the condenser at the beginning and end of the time may be measured with a ballistic galvanometer, and the resistance calculated from $r = \dfrac{t}{\text{K}\log_e \frac{\text{D}_1}{\text{D}_2}}$, D_1 and D_2 being the deflections obtained on the galvanometer.

THE WHEATSTONE BRIDGE.

If we have two points, P_1 and P_2, between which a constant difference of potential is maintained, then by connecting these two points through a conductor a current entering the conductor at the point of higher potential, say P_1, gradually falls in potential as it passes from P_1 to P_2, and in so doing passes successively through every conceivable potential whose value lies between that of P_1 and P_2. Let us make this plain by some simple numbers. If P_1 be at a potential of 4·5 volts and P_2 at 1 volt, and we connect a wire whose resistance is 7 ohms, from P_1 to P_2, we shall clearly get a current of half an ampere. What we have stated above amounts to saying that since such a value as 2·67894 lies between 4·5 and 1, and since the current enters at a potential of 4·5 and the potential decreases till it reaches 1, it must in the process pass through the value we have just given; hence if we can only find the right point, we can certainly find a point where it has that precise value, namely, 2·67894. Now this is not true merely of one wire; but if we connect others between the same two points, then current will enter these wires at one end at a potential of 4·5 volts and leave them at a potential of 1. Hence the potential of the currents through them will also pass through the value above mentioned, and possibly we may be able to locate the point in these wires where the potential was precisely of the value named. If we can find these points, one in each of two wires, then clearly, since they are at the same potential, no current will flow between them, even if they be connected by a conductor. Let us just examine the conditions under which the two points so connected would be at the same potential. We will take a special case in the first instance, one in which the two points are to be at a potential of 3·5 volts. In the first wire, which takes half an ampere, we have to find a length whose resistance is 2 ohms, since the half ampere will drop one volt in traversing this resistance. Let the first wire, of 7 ohms be 350 inches long and let the second be 420 inches long with a resistance of 14 ohms. In the first wire 2 ohms will be the resistance of 100 inches and the point we desire will be 100 inches from the 4·5-volt point. In the second wire, which carries a quarter of an ampere, we shall clearly have to travel down a length whose resistance is 4 ohms, and as the wire is 420 inches, with a resistance of 14 ohms, the point we wish will be 120 inches from the 4·5-volt point. On inspection we see that the point we have determined divides the upper wire into two lengths, one of 100 and the other of 250 inches, while the point located in the lower wire divides it into lengths of 120 and 300 inches respectively. A certain correspondence between the two cases is at once obvious, for we see that the point found in each wire is exactly two fifths of its length from the 4.5-volt point. We have taken lengths of wire in the above calculations because we assume the wire to be uniform in diameter, the quantities with which we really were concerned being the resistances of those lengths; hence, if we consider the upper wire to be sub-divided into resistances proportional to the lengths, the relationship that we have just noted is that $\frac{R_1}{R_2}$ is equal to $\frac{R_3}{R_4}$. This, then, is the whole principle involved in the Wheatstone bridge, a principle which has proved of untold service to electricians. It affords us, in fact, at once the simplest and most accurate method we have of measuring all resistances lying between about one ohm and one million ohms. Resistances which

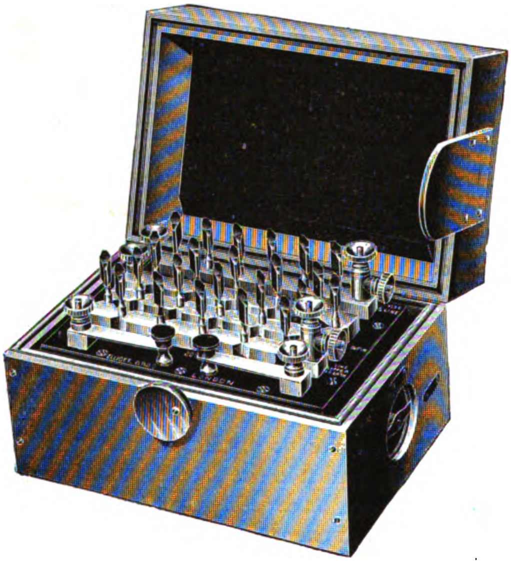


FIG. 273.—POST OFFICE PATTERN OF WHEATSTONE BRIDGE.

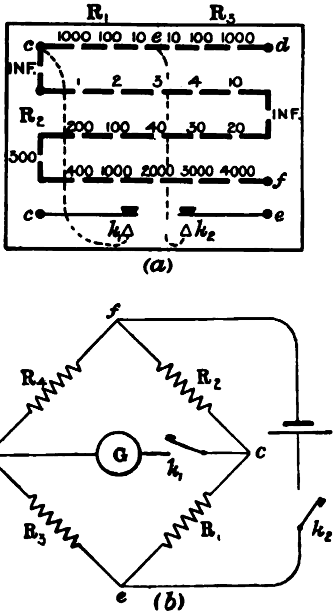


FIG. 274.—CONNECTIONS OF WHEATSTONE BRIDGE.

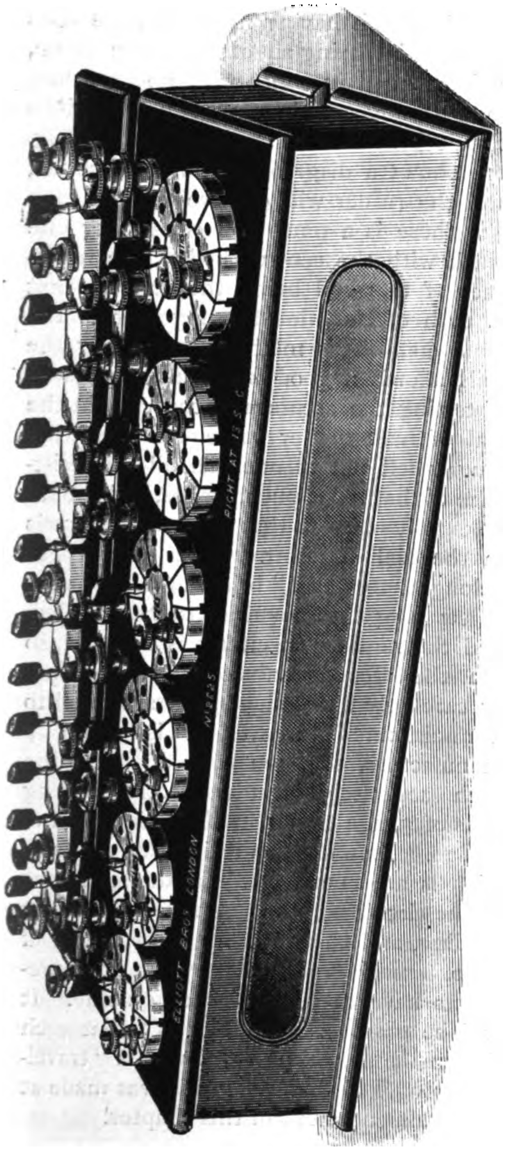


FIG. 275.—DIAL FORM OF WHEATSTONE BRIDGE.

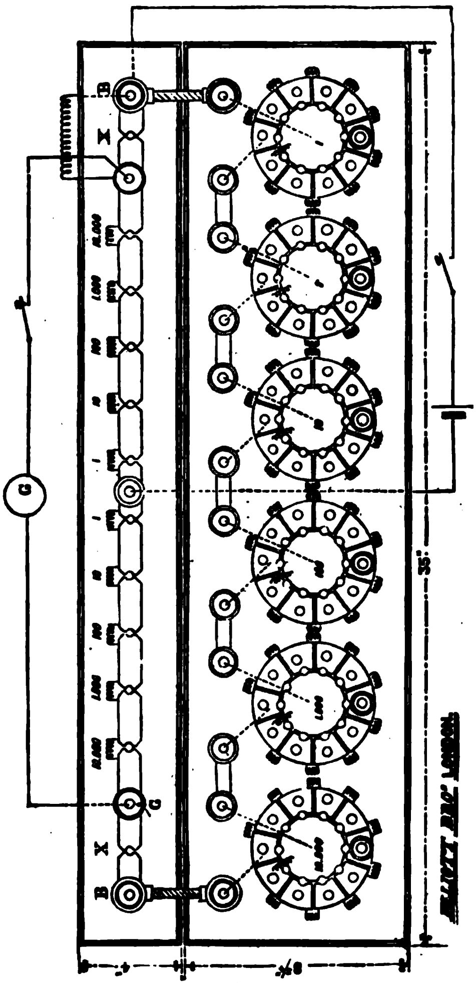


FIG. 276.—CONNECTIONS IN DIAL PATTERN OF WHEATSTONE BRIDGE.

are less than one ohm may indeed be measured by the bridge, and resistances that are above one million ohms may be roughly measured by the same means. Those above one million ohms are better measured by direct comparison with a standard megohm or by means of an ohmmeter. Resistances whose values are below one ohm may be well measured with a bridge down to one-tenth or even one one-hundredth of an ohm, but it is preferable for those below one-tenth, and almost imperative for those below one one-hundredth, to employ some other means.

For convenience in testing, the Wheatstone bridge is made up with R_1, R_2, and R_3 in one box, this arrangement being known as the "Post Office" form. This is shown in Fig. 273, and a diagram of its connections in Figs. 274 (*a b*). The arms, R_1 and R_3, of which only the ratio need really be known, are *e c* and *e d*. R_2, is *c f*, and R_4, the unknown resistance, is joined to *d* and *f*. The battery is connected through its key to *e* and *f*, and the galvanometer through its key to *c* and *d*. When using the bridge, the key k_2 making battery circuit, should always be depressed first, the galvanometer circuit being closed afterwards, for if the order be reversed there may be a kick on the galvanometer due to self-induction effects. Also the most sensitive arrangement of the bridge is when all four arms are equal, that is to say when $R_1 = R_2 = R_3 = R_4$. For very accurate bridge work, where thermal effects might possibly enter into consideration, it is as well, after obtaining balance with the current in one direction, to reverse its direction and again obtain balance. By taking the average, the thermal effect is eliminated.

THE DIAL BRIDGE.

Fig. 275 shows another form of bridge in which the method of inserting resistances differs somewhat from that previously described, inasmuch as when a plug is inserted the resistance is brought into circuit and not short-circuited as in the ordinary form of box. The box contains six dials, each having nine coils, the coils in one dial being all of the same value, and arranged in series with one another, so that any numbers may be put into circuit by means of one plug only. Fig. 276 shows a diagram of the connections, and the reader will observe that in each dial there is a tenth coil connecting one block with the centre portion, the resistance of this coil being the same as that of each of the nine forming part of the same dial. This method of grouping the coils affords a good and convenient way of testing the accuracy of the coils in the dial of next higher value, for when the plug is left out in one dial, all the resistance of that set is put in series, and should be exactly equal to that of one of the coils in the dial above it. Other advantages belonging to "Dial" bridges are that only a few plugs are required to be handled, and the number in circuit is constant, so that the errors introduced by badly-fitting or carelessly-inserted plugs are reduced to a minimum; moreover, it is easier to manufacture, say, ten coils of one ohm each accurately than the corresponding coils of 5, 2, 2 and 1 in the older form or bridge. Another point is that the sets of coils are so arranged that the resistance in the circuit may be ascertained by direct reading, and this means a great saving of time, especially where several measurements have to be performed quickly. It will be observed from Fig. 275 that each dial in the box is provided with a "travelling plug," of which mention was made at the commencement of this chapter.

THE DIFFERENTIAL GALVANOMETER.

The great range of the Wheatstone bridge and the introduction of extremely sensitive reflecting galvanometers, which can be used either with the bridge or with a potentiometer, caused the original pivoted form of differential galvanometer to fall into disuse and into a certain amount of disrepute, in consequence of which many attempts were made to introduce the use of a reflecting form of differential galvanometer. These efforts met with obstacles arising from the great difficulty in properly adjusting so delicate an instrument to be truly differential. If the instrument is to be of much use the two coils must be exceedingly carefully made with reference to absolute equality of resistance, of number of turns, and of mean distance from the suspended magnet. These conditions having been duly fulfilled, the further adjustment of the instrument consists in suspending the magnet system so that it is truly central in the coil or central to the two coils, and, when it is set up, in preserving the level with great accuracy so that the magnet system shall be central and in the median plane. Such adjustments take a considerable amount of time and patience, and despite great care in manufacture the two coils will not, when the same current is passing through them in opposite directions, have precisely equal actions on the magnet.

The tests which are to be made to determine whether or not a differential galvanometer is in proper adjustment can be carried out in the following way. First of all, determination should be made as to whether the same current flowing in the two coils so as to produce opposing forces on the magnet produces deflection or not. Properly, of course, there should be no deflection, but if the two coils have not precisely equal mean distance from the magnet, or if there is even a fractional difference in the number of turns, the same current in the two coils will cause one to predominate over the other, and there will be a slight deflection in the one direction or the other, depending upon which of the two coils predominates. Clearly the simplest and most accurate way of making this determination is by connecting the two coils in series so as to oppose one another, and if a deflection is produced when current is sent through them it may be due either to the turns not being identical in the two coils or to the magnet system not being placed symmetrically in reference to them. The former defect is one of manufacture and cannot be immediately remedied. The latter, on the other hand, may be but merely due to faulty adjustment, and may possibly be rectified by careful levelling. This should therefore be at once resorted to, and the effect of varying the adjustment of the levelling screws tried. As a rule, it is possible by patient attention to this detail to bring the instrument into adjustment for no deflection when the two coils are in series and opposing. If, however, the instrument is

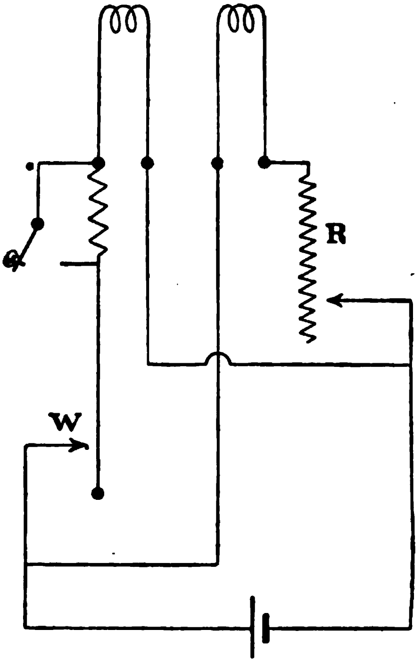


FIG. 277.—CRAWLEY'S METHOD OF USING DIFFERENTIAL GALVANOMETER.

to have wide range of use it should not only produce no deflection when the two coils carry equal currents, but also when they are connected in parallel and served with one and the same E.M.F. This, of course, after the former adjustment has been made involves absolute equality of resistance in the two circuits. If, as is usually the case, the resistance of each coil exceeds 100 ohms, a fairly satisfactory test may be made by connecting the two coils in parallel so as to oppose one another, using for the connection stout bare copper wire.

In a general way the sensitiveness of a reflecting galvanometer is so great that it is capable of indicating inequality of resistance in two circuits under test to a much greater degree of accuracy than is really useful, and Mr. Crawley has described a method of using the galvanometer which permits of extremely accurate results being obtained without necessitating any very extreme care in the preliminary adjustments, and again without necessitating an absolutely null method of use. Mr. Crawley connects the galvanometer as indicated in Fig. 277, inserting a resistance as shown in each of the coil circuits: that in one of the circuits may be any convenient and roughly adjustable resistance box, while that in the other coil should bear a definite ratio to the resistance of the coil, and should further include a resistance capable of very fine adjustment. A slide wire fulfils the latter condition excellently. It is indicated at W. The other portion of this external resistance may conveniently bear a ratio to the resistance of the coil of 1 to 1,000, and is provided with a short-circuiting key. The galvanometer is then adjusted in the following way: the two coils are connected in parallel opposing one another, and current supplied from a battery, and by means of the resistance box, R, and slide wire, W, the currents in the two circuits are adjusted without reference to their precise equality, until there is practically no deflection. If, now, the short-circuiting key be closed, the balance is disturbed by one-tenth of one per cent. and a deflection is produced which will ordinarily amount to 200 or 300 scale divisions. This, then, is a measure of the want of balance, and if the deflection be 250 scale divisions for a 0·1 per cent. want of balance, 25 divisions will be the deflection produced by one-tenth of this discrepancy. Hence, if resistances are to be adjusted to within this limit of accuracy, namely, 0·01 per cent. either way, all that need be done is to test them on the galvanometer and adjust them until the deflection produced does not exceed 25 divisions on either side of zero. If double the accuracy is required the deflections must not exceed half that amount, namely, 12 divisions either way, this degree being sufficient for all ordinary purposes.

CAREY-FOSTER'S METHOD.

THIS method of measuring resistance is of particular value for the accurate comparison of two resistances which are very nearly equal, hence it is of service when a number of coils are in course of manufacture, and are all intended to be of some standard value, in the manufacture, for example, of the dial form of Wheatstone bridges where each bridge contains sets of nine equal coils, such as nine 0·1 ohm coils, nine 1 ohm coils, nine 10 ohm coils, and so on. The method consists in making connections as shown in Fig. 278 to a Kirchoff metre bridge employing also two unknown resistances R_1 and R_2, which may be made up in any rough-and-ready fashion so as to be equal. It is advisable to make these unknown resistances of material with a low temperature coefficient, such as platinoid or eureka, although this is not absolutely necessary. They may be made by cutting off nearly equal lengths of the wire and coiling them roughly on boards. The slight inequality in the resistance of these two lengths of wire is the basis of the method of the test; hence if one of them heats from any cause whatever more than the other, the magnitude of the inequality will change and the test will be interfered with. Such unequal heating is, of course, very unlikely to occur; but since it is so easy to procure materials having low temperature coefficients nowadays, it is just as well to take the precaution to use them for this test. In the diagram S_1 represents the standard coil with which S_2 is to be compared, and to which, in point of fact, S_2 is supposed to be equal. S_1 and S_2 have subsequently to change positions, and it is of the utmost importance that the contact resistance of the connections to these coils should be entirely negligible during the test. For this purpose it is usual to provide the Foster bridge with terminals consisting of mercury cups made of copper well amalgamated. Standard resistances are almost invariably supplied by their makers with electrodes consisting of stout rods of copper, the ends of which have been amalgamated. These are intended for dipping into the mercury cups of a Foster bridge; and, indeed, the connections to standard resistances should invariably be made by this means, in order, as has been pointed out, to eliminate contact resistance as far as possible, and in so far as it is not eliminated to make it sensibly constant. The two standards S_1 and S_2 having been put into circuit by their respective mercury cups, bridge balance is obtained in the usual way by adjusting the position of the tapping point of the key upon the bridge wire. Balance having been obtained with S_1 and S_2 in the position shown in the diagram, they are then interchanged and balance is again obtained. The resistance of the piece of the bridge wire lying between the two points at which balance was obtained in the two cases is the difference between the resistances of S_1 and S_2. That this is the case may readily be seen from the various relationships based on the theory of Wheatstone's bridge.

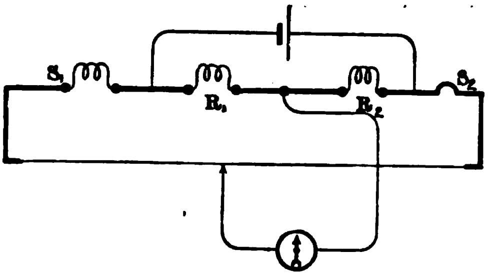


FIG. 278.—CAREY-FOSTER BRIDGE.

Carey-Foster's method may be employed by a simple adaptation for the calibration of the slide wire of a metre bridge. It is of great importance that the slide wire should be either of absolutely uniform resistance per centimetre of its length, or at least that any variation in its resistance per centimetre should be accurately known.

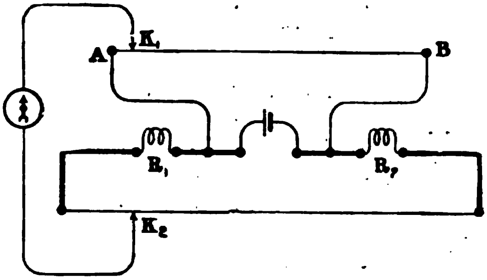


FIG. 279.—CONNECTIONS FOR CALIBRATION OF BRIDGE SLIDE-WIRE.

In order to calibrate the slide wire of a bridge its whole resistance should first be accurately measured by Wheatstone's bridge or some such arrangement, and it should then be connected up with another slide wire and key, as shown in Fig. 279. Two resistances, R_1 and R_2, of unknown value, but approximately equal to one another, are employed as before, and connection must be made with them by means of mercury cups. The key of the bridge to be tested is placed near to one end of the wire, and balance is obtained by moving the key, K_2, of the other bridge in the usual way. R_1 and R_2 are then interchanged and without moving the key K_2 from the position in which balance was obtained, the disturbed balance is restored by moving the key K_1. Balance having been obtained, R_1 and R_2 are again interchanged, and the disturbance is eliminated this time by moving K_2. This cycle of operations is repeated until the key K_1 has traversed the whole length of the slide wire. The result of the operation is to divide the slide wire under test into portions of equal resistance, and since the whole resistance was measured before commencing the test, we know now the value of the resistance of each little portion into which the wire has thus been divided.

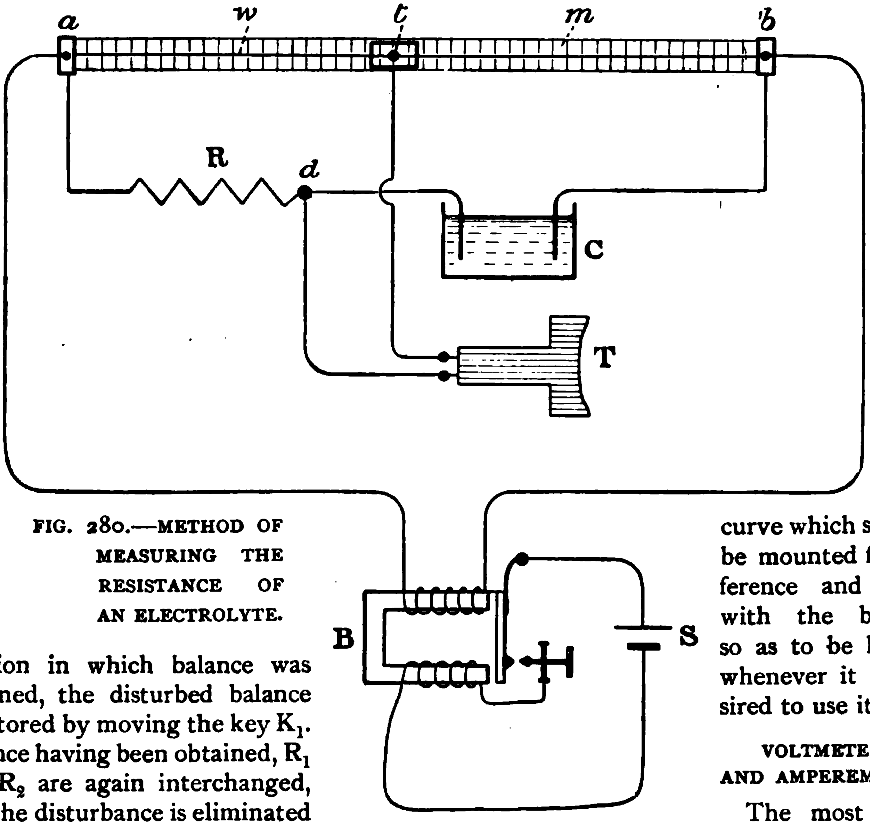


FIG. 280.—METHOD OF MEASURING THE RESISTANCE OF AN ELECTROLYTE.

The resistance of each portion is equal to the difference between R_1 and R_2, so that the more closely the resistances of these two approximate to one another, the greater will be the number of lengths in which the slide wire has been divided, and the greater, therefore, the general accuracy of the result. When a wire has thus been calibrated the result should be embodied in a curve which should be mounted for reference and kept with the bridge, so as to be handy whenever it is desired to use it.

VOLTMETER AND AMPEREMETER.

The most common way of measuring low resistances is by means of a voltmeter and amperemeter. The low resistance is connected in series with an ammeter and a source of current. With a known current flowing, the voltage across the resistance is measured by means of a low reading voltmeter. The resistance at once follows from Ohm's law $R = \frac{E}{C}$. This method finds a general application in the test room for measuring the resistances of the armatures, and compounding coils of dynamos or motors, and low tension windings of transformers.

There is still another kind of resistance which sometimes has to be measured, and that is the resistance of an electrolytic bath. Any method which involves sending an ordinary unidirectional current through the bath causes polarisation, which entirely vitiates any results that may be obtained, in addition to the trouble caused by the E.M.F. of polarisation. The simplest way by which this measurement can be effected is by employing a form of Wheatstone bridge, and using a current which is not unidirectional; Fig. 280 shows the method of connecting up for making this measurement. The ratio arms of the Wheatstone bridge are formed by a stretched wire, *w*, the ratio being changeable by moving the sliding contact piece, *t*, along the scale, *m*, which is graduated in centimetres. The resistance which, in the ordinary bridge is adjustable, is replaced by a fixed resistance, R, and C, the electrolytic cell, constitutes the fourth arm. The place of the galvanometer is taken by the telephone receiver, T, which is connected across *d*,*t*. The source of alternating supply is connected to the terminals, *a* and *b*, and may be the secondary of a small induction coil from which the condenser has been removed, or even alternating current mains, if a suitable resistance be placed in series with the test apparatus.*

When the receiver is held to the ear, if balance has not been obtained, a loud sound will be heard. By moving the contact, *t*, along the stretched wire this sound decreases to a minimum, and upon further movement in the same direction increases again. The position of least sound in T is the position of balance. The lengths, *b t* and *t a*, of the wire, give the ratio between R and C, whence the resistance of the bath C can at once be calculated. The use of an alternating current enables a telephone receiver to be used and prevents any polarisation.

THE MEASUREMENT OF E.M.F.

For rough measurements of E.M.F. one of the voltmeters described in Chapter III. of this section will, as a rule, suffice. It is of great importance, however, in the accurate measurement of E.M.F.'s, to note that any instrument or any method of measurement which makes a demand for current from the source whose E.M.F. is to be measured introduces an error by reason of the internal resistance of the generator. In speaking of the E.M.F. of a generator, what is referred to is the actual E.M.F. when the generator is delivering no current whatever; or if it be delivering a current, then what is referred to is the internal or generated E.M.F., as distinct from the terminal E.M.F. or voltage of the generator. Now this latter quantity, if the generator be sending any current whatever, clearly differs from the internal or generated E.M.F. by an amount which is proportional both to the internal resistance and to the current being sent. Where either of these quantities, therefore, is exceedingly minute its product is also, as a rule, negligible, and hence methods which demand an exceedingly small current may for most purposes be applied with sufficient accuracy. What is meant by an exceedingly small current is, one which is exceedingly small in comparison with that which the generator is designed to deliver. Hence a voltmeter taking a current of, let us say, one-third of an ampere would be a perfectly satisfactory instrument for measuring the voltage of a large dynamo machine, but would be quite unsuited for the measurement of the E.M.F. of a battery of primary cells.

---

* The author finds a very convenient source of alternating current for this purpose is obtained by disconnecting one coil of an ordinary electric bell, and using this as a source, the remaining coil serving to make the armature vibrate in the ordinary way, by means of a battery. The contact screw should be adjusted to give as rapid vibrations as possible, the hammer being removed.

A device commonly employed is a resistance box of high range and accurately sub-divided. An ordinary standard resistance box up to, say, ten thousand ohms, serves excellently. In addition to the ordinary plugs the box is provided with two travelling plugs such as have been described on p. 303. The ordinary plugs are withdrawn until, say, ten thousand ohms are in, made up not of one coil but of coils of as many different values as can be arranged. For example, with the ordinary arrangement there would be one 5,000, two 2,000's, one 500, two 200's, one 50, two 20's, one 5, two 2's, and one 1 left in circuit. The maximum E.M.F. to be employed is then applied to the terminals of the box, and by placing the travelling plugs at a suitable distance apart, any desired sub-multiple of the maximum E.M.F. may be obtained. The precise ratio of this sub-multiple to the total is simply the ratio of the resistance lying between the travelling plugs, to the total resistance, say ten thousand ohms, in circuit in the box. Connection is made from the travelling plugs by means of flexible conductors to the apparatus to be tested. The resistance of the path through the apparatus should be at least ten times that lying between the travelling plugs, which should preferably be arranged to take no current whatever, by one of the well-known methods given below. Such methods are called "null" methods. The calculations are exceedingly simple, particularly if care is taken to make the total resistance in circuit in the box a good round number, such as one, ten, or one hundred thousand. The use of a resistance box in this manner is very common, and it is said then to be used as a potentiometer; any device which will provide sub-multiples of a given maximum E.M.F. at its terminals, by enabling known portions of the resistance, down which the E.M.F. is at work, to be tapped, being known as a potentiometer.

A potentiometer of this kind can be applied very simply to the measurement of E.M.F., the E.M.F. to be measured, if large, being connected across a large known resistance, and a tapping being taken across a known small portion, as described. The voltage across this tapping is varied by adjusting the tapping, and is then balanced against a standard cell, and again varied if necessary, until the two are equal; then, since the ratio to the total E.M.F. is known, this latter is at once calculable. This method is well illustrated in the following way of calibrating a voltmeter.

CALIBRATION OF A VOLTMETER BY STANDARD CELL.

As in the calibration of all other instruments the simplest method is, of course, that of direct comparison with a standard instrument when such an instrument is available. If, however, a really accurate standard is not available, some one of the following methods must be employed.

The connections are to be made as in the accompanying diagram, Fig. 281, where MM represent two main leads giving current at a pressure sufficiently great to take the voltmeter over its whole range. C is a

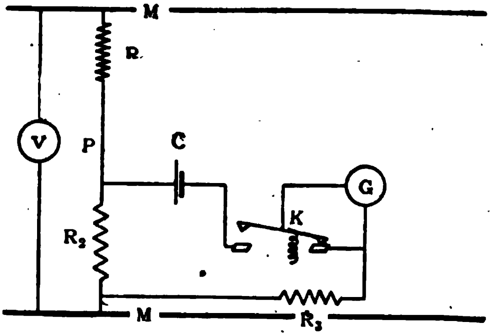


FIG. 281.—CONNECTIONS FOR THE CALIBRATION OF A VOLTMETER BY STANDARD CELL.

standard cell, either a Fleming or a Clark, preferably the former, since it is less liable than the latter to temporary derangement from the currents which of necessity flow during the preliminary adjustments. P is merely a sub-divided resistance connected across the mains MM, which enables us by tapping it at suitable points to supply a voltmeter with any voltage less than the total voltage of the mains, so that deflections may be obtained over the whole range of the scale. R_1 is a resistance of ten thousand ohms, R_2 is a resistance of about a thousand ohms, capable of adjustment by means of plugs in the ordinary way, and connected in series with R_1. R_3 is a resistance which is permanently in the circuit of the galvanometer G, and which merely serves to protect the latter from excessive currents during the preliminary adjustments when the want of balance may give rise to a comparatively large P.D. across the terminals of the galvanometer circuit. The galvanometer must be a sensitive one, and should be preferably dead beat. A D'Arsonval galvanometer with the coil wound on a metal bobbin or enclosed in a metal tube is the most suitable for the purpose. It should be wound to have a resistance of about 500 ohms in order to be sufficiently sensitive. The key K is a Morse key, which in the at-rest position short circuits the terminals of the galvanometer, and when tapped connects the galvanometer in series with the standard cell across the terminals of R_2. The voltmeter is connected, as shown, across the ends of R_1 and R_2, which are permanently in series. The method adopted is that of balancing the fall of potential down R_2 against the E.M.F. of the standard cell, the galvanometer indicating when this has occurred by showing no deflection when the key is tapped. The method is thus what is called a null method, and is susceptible of great accuracy. Care must, of course, be taken to ensure that the E.M.F. of the standard cell is in opposition to the P.D. down R_2, since if this be not the case it is quite clear that no amount of adjustment can possibly give no deflection when the key is tapped. The sensitiveness of the arrangement depends, apart from the sensitiveness of the galvanometer, upon the fineness with which R_2 may be adjusted, and also upon the ratio which R_2 bears to the sum of R_1 and R_2. For this reason alone it is preferable to employ a cell having a low E.M.F., such as a Fleming or Weston, rather than a Clark cell. The current flowing down the circuit containing R_2 is clearly equal to $\frac{V}{R_1 + R_2}$ where V stands for the voltage across the terminals of the voltmeter. Hence the fall of potential down R_2 is equal to that current multiplied by R_2. Now when balance has been obtained by adjusting the value of R_2 this fall of potential is equal to the E.M.F. of the standard cell, and if this be the Fleming cell (*see* page 242) we may write

$$\frac{V}{R_1 + R_2} \times R_2 = 1{\cdot}072 \text{ or}$$

$$V = 1{\cdot}072 \left(\frac{R_1 + R_2}{R_2}\right)$$

VOLTMETER CALIBRATION BY CROMPTON POTENTIOMETER.

The calibration of a voltmeter by this method is fully explained in the paragraph describing the instrument (*see* page 342)

BY ELECTROMETER.

In this method the connections have to be made as shown in diagram No. 282, where R_1 is a resistance box ranging from about one to ten thousand ohms, and R_2 a similar box which need not, however, have quite such a high range. E is the electrometer and s a standard cell. The electrometer is first of all calibrated in the following way, so that the meaning of its deflections is accurately known.

If the standard cell employed be a Clark cell the total resistance in R_2 may be appropriately 1434·1 ohms, and the electrometer is connected across ten ohms of this box. On pressing the key, K_1, a deflection on the electrometer is produced corresponding to a potential difference of 0·01 of a volt across its terminals, and thus the scale is calibrated. The voltmeter is now connected across the terminals of R_1 and supplied with a potential difference suited to the range of the instrument. The electrometer is now connected to two points in the box R_2, and the distance between these points in ohms is adjusted until either the deflection is again what it was when connected to R_2, or until the deflection obtained is of some value corresponding to a known voltage. For convenience and rapidity of operation it is advisable continually to readjust the total amount of resistance in the box R_1 until the number of ohms contained in it corresponds in some simple way with the indication of the instrument. For example, if the voltmeter indicates 9·57 volts it will be convenient to put in 9,570 ohms in R_1, in which case if the electrometer be connected across ten ohms of R_1, it should indicate 0·01 of a volt if the voltmeter is correct. If the voltmeter be not correct, the true reading is at once obtained by multiplying its reading by the ratio of the electrometer deflection obtained, to the deflection that would have been obtained with 0·01 of a volt.

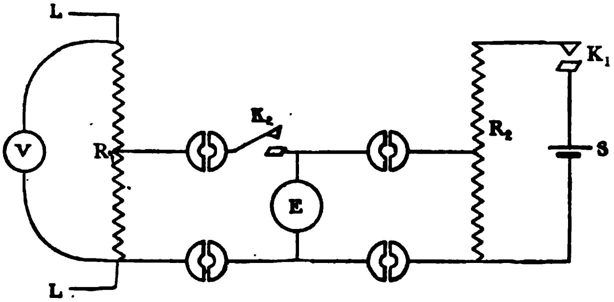


FIG. 282.—CONNECTIONS FOR CALIBRATION OF A VOLTMETER BY AN ELECTROMETER.

BY MILLIAMMETER OR MILLIVOLTMETER.

A milliammeter may be employed to calibrate a voltmeter with great rapidity if accurately known resistances are obtainable, and provided the voltmeter is of a type which does not demand a great current. The method is especially suitable for electrostatic voltmeters, but is also suitable for voltmeters of the Weston type. A preliminary test has to be made of the current taken by the voltmeter throughout the range for which it is to be calibrated, by connecting the milliammeter in series with the voltmeter, and noting the current passing corresponding to indications of the instrument at numerous points on its scale. Connections are then made as in Fig. 283. The accurate adjustable resistance is connected in series with the milliammeter, and the voltmeter is connected across the terminals of the resistance; varying voltages are then supplied in succession to the points marked T_1 and T_2 in the diagram, and at each voltage the current passing in the milliammeter and the value of resistance R carefully noted. It is convenient in carrying out this test to so adjust the resistance at each reading of the volt-

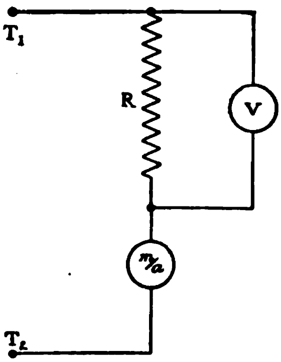


FIG. 283.—CALIBRATION OF VOLTMETER BY MILLIAMMETER.

meter so that the current flowing in the milliammeter is just equal to the current taken by the voltmeter *at that reading* plus some convenient constant amount. The precise value of this amount depends, of course, upon the carrying capacity of the accurate resistance, upon the range of the milliammeter, and upon the current demanded by the voltmeter. If, however, it can be adjusted to say, ten milliamperes, the calibration will be a very rapid matter. In this case, when the current through the voltmeter has been deducted, the current through the resistance will always be ten milliamperes, and hence the different voltages across the terminals of the voltmeter will be one one-hundredth of the respective resistances in the box in ohms.

BY MILLIVOLTMETER.

A millivoltmeter may be used as follows. It is connected to the ends of a standard one hundred ohm resistance, and the millivoltmeter, and the resistance in parallel, are then connected, as shown in Fig. 284, in series with an accurate adjustable box, across the terminals of which is also connected the voltmeter to be calibrated. The pressure between the terminals T_1 T_2 is varied, and with every variation the value of the adjustable box is changed until the millivoltmeter indicates, say, ten millivolts. Any other convenient constant value can be taken, but if this is suitable to the ranges of the various pieces of apparatus employed, it will give rapid results. Clearly, if there be always ten millivolts across the standard one hundred ohms, the voltage across the adjustable box will very approximately bear the same proportion to ten millivolts that the resistance in that box bears to one hundred ohms. This ratio, however, will only be approximately correct, since the millivoltmeter itself takes some current, and hence the current through the adjustable box is greater by that amount than the current through the one hundred ohms. If, however, very great accuracy is not desired, the method is satisfactory, provided a modern well-designed millivoltmeter be employed. The current in such an instrument would not exceed twelve milliamperes at ten millivolts. Should, however, great accuracy be required, a correction is very easily introduced for the current passing down the millivoltmeter, since the millivoltmeter is always adjusted to the same reading, the current through it is constant, and this current should be measured once and for all. The addition to the voltage as first computed must then be made, the voltage down the adjustable box being really greater than as first computed by an amount equal to the millivoltmeter current multiplied by the resistance in the box. For commercial instruments this method is, as a rule, amply accurate.

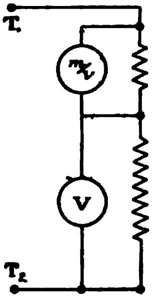


FIG. 284.—CALIBRATION OF VOLTMETER BY MILLIVOLTMETER.

RAYLEIGH'S METHOD.

This method of measurement of E.M.F. of a battery is given here as a good example of a device by which the true internal E.M.F. of a cell may be arrived at although current is taken from it. The connections for this test are shown in Fig. 285, where B_1 is the cell to be tested, B_2 a standard cell, C a condenser, G a galvanometer, and K a key. P is a two-way plug. On examining the diagram of connections it will be seen that if the plug be inserted in the hole marked 2, the standard cell B_2 is put in circuit in series with the condenser, the galvanometer, and the key. The key is of a particular kind known as a charge and discharge key, specially constructed for use with condensers. When the key is depressed the

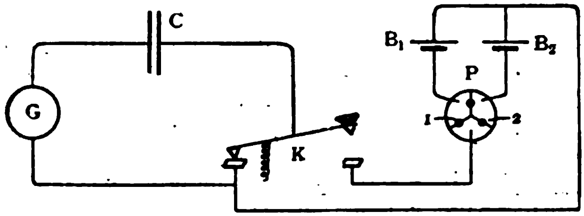


FIG. 285.—RAYLEIGH'S METHOD OF MEASURING E.M.F. OF A BATTERY.

cell is connected through the key to one side of the condenser hence the charge entering this side of the condenser displaces an equal and opposite one from the other side, which passes through the galvanometer and causes it to deflect. When the key is released it returns to the position shown in the diagram, and by so doing short circuits the condenser through the galvanometer, thus discharging the condenser through the galvanometer, and imparting to the latter a deflection equal to, but opposite to that given by the charge. The plug is now removed from the position marked 2 and inserted at 1, and the process just described in connection with the standard cell is repeated for the cell under test. The galvanometer employed has to measure the relation between the charge imparted to the condenser by the standard cell and that given by the cell under test. Now the charge imparted to a given condenser (*see* page 9, Section I.) is equal to the capacity of the condenser multiplied by the voltage across the terminals of the condenser. When the key is first put down, the condenser having been previously discharged, there is at the first instant virtually no resistance whatever in the path of the current beyond the internal resistance of the battery, and that offered by the connecting wires. There is hence a considerable rush of current, but this is immediately checked by the back E.M.F. in the condenser, which rises as the charge enters, as will be clearly understood by a reference to the passage in Section I. above referred to. The rise of the back E.M.F. of the condenser reduces the current, and hence there is a reduction in the loss of voltage caused by the internal resistance of the battery. This means that the terminal voltage is now more nearly equal to the internal E.M.F., and as this rises so a small additional charge is forced into the condenser. This process goes on, the current falling off and the terminal voltage rising until a state of affairs is reached when the back E.M.F. of the condenser is precisely equal to the forward E.M.F. of the cell, and no current passes in either direction. This occurs as a rule in ordinary circuits in a space of time which is but a minute fraction of a second, so that the condenser may be considered to become charged to its full extent practically instantaneously; but it is of great importance to note that it only receives the full E.M.F. of the cell by virtue of the fact that the current dies down to nothing in the process of charging. Now the galvanometer, as we have just seen, has to measure the total quantity of charge, and must be suited for ballistic work. The needle will not begin to swing until the whole of the charge has passed through its coils, and what we have to note is the extent of its first swing or throw. We clearly cannot have, if everything is in order, a steady deflection on the galvanometer, since, as we have above remarked, directly the condenser has been charged there is no more current flowing in the circuit. The first swing or throw of the galvanometer is carefully observed when the key is depressed, and the key is then held depressed until the galvanometer needle has come absolutely to rest. The key is then released and the swing due to the discharge observed. If the condenser is in order and made of good material the throw due to the discharge will be equal to that caused by the charge; if it be not exactly equal the process should be repeated once or twice, and the mean of all the readings taken. The series of operations is then repeated for the cell to be tested, and the ratio of the mean throw of the cell to be tested to that caused by the standard cell will give the ratio between their E.M.F.'s.

THE MEASUREMENT OF CURRENT.

This can, of course, be effected with the ordinary ammeters, described in the instrument section, or for laboratory work, when dealing with small currents, with the tangent galvanometer described on page 244, *et seq.* An accurate method of current measurement, but one more suitable for calibrating ammeters by comparison than for direct reading, is afforded by the Kelvin current balance, described on page 270.

THE COPPER VOLTAMETER.

For all cases where the utmost accuracy is not required, and where a special instrument is not available for comparison, the copper voltameter affords the most reliable means for absolute calibration. Where exceedingly high accuracy is required a silver voltameter is preferable, or even for very small currents a zinc iodine voltameter. For large currents, however, the silver voltameter becomes somewhat costly, and the copper voltameter will with care yield results having all the accuracy desired in commercial and in ordinary laboratory practice, and, moreover, these results may be obtained cheaply and by persons of limited experience. The points to be observed to secure accuracy in the use of the copper voltameter are, firstly, to avoid fingering the cathode plates except by means of forceps, and then only at parts which do not have to be immersed. Secondly, to avoid having too high a current density, and at the same time to avoid one of too low a value. A current density of about 20 amperes per square foot gives very good results. Thirdly, to remove the cathode from the bath the instant current is stopped, and to wash and dry the cathode with the least possible delay. Fourthly, to prevent oxidisation of the cathode on its removal from the bath by every possible means, such as by rapid and thorough washing and drying and by rapid weighing. An excellent solution may be obtained by dissolving 15 ounces of recrystallised copper sulphate in 100 ounces of water, and then adding successively 5 ounces* of strong sulphuric acid, 5 ounces of alcohol (not methylated spirit). This solution should be made up with distilled water by preference, and kept covered over when the bath is not in use. With this solution Oettel claims good results can be obtained with any current density lying between 6 and 140 amperes per square foot of cathode. The cathode must be thoroughly cleansed by emery paper, pumice powder, by being well rinsed, and finally by being swilled in diluted potassium cyanide, from which it is again rinsed. It should then be suspended in the bath and the current carefully adjusted to the first value at which the ampere meter has to be calibrated, and the current is allowed to flow for a sufficient time to cover the cathode with a clean uniform coating which should have a clear salmon pink colour. The cathode is then removed at once, swilled in water, and thoroughly rinsed from all traces of the bath solution, and may then be dried in warm filter paper. Cold filter paper will do, but there must be plenty of it, and drying must be effected as rapidly as possible. Some workers advocate drying over a Bunsen flame, but unless this is done with extreme care it is likely to accelerate oxidisation, and hence introduce error. The error caused by oxidisation is independent of the depth of the coating, since it is only a surface of practically uniform depth, and the error due to it is hence reduced in importance by increasing the thickness of the deposit. It is therefore advisable to keep the current flowing as long as is reasonably convenient. In order to be sure that the current does not vary during the reading, observations on the amperemeter should be noted at least every minute, and preferably every thirty seconds, and if the amperemeter has much friction at the pivots it should be tapped at each reading to eliminate the friction as much as possible. For the subsequent readings a somewhat tedious procedure, but one which the author recommends, is to adjust the current strength with the cathode in position before commencing the reading. This entails re-weighing of the cathode, or at any rate a re-counterpoising, which is avoided by the use of substitutionary resistances, or by the rough method of adjusting the current during the time really occupied in the reading. The method recommended, although tedious, has the advantage of giving thoroughly satisfactory results, which can, as a rule, be relied upon for very considerable accuracy.

---

* *Not* fluid ounces.

MEASUREMENT OF CAPACITY.

A description of the methods involved in making an absolute measurement of capacity with any degree of accuracy is entirely beyond the scope of this work. The method adopted for general use is by comparison with a standard condenser of known capacity.

COMPARISON BY BALLISTIC GALVANOMETER.

If two condensers are charged to the same potential, the quantity of electricity in each is proportional to their capacities. Thus, if the quantities be measured, and the capacity of one condenser be known, that of the other can be simply calculated. Fig. 286 shows the connections necessary for this method of working.

C_1 is the capacity to be measured ;

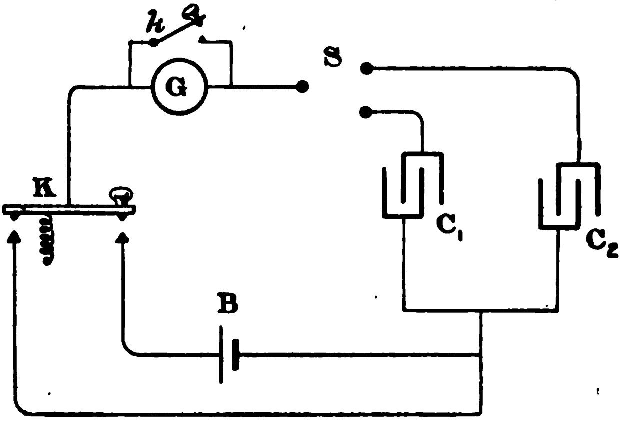


FIG. 286.—MEASUREMENT OF CAPACITY.

C_2 is a standard capacity, say ⅓ of a microfarad ;

K is a charge, isolate, and discharge key ;

S is a two-way plug key, by which either capacity can be put in circuit ;

B is a primary battery ;

G is the ballistic galvanometer, fitted with short-circuiting key, *k*, for bringing it rapidly to rest.

With the standard condenser in circuit, the key, K, is depressed, and the deflection obtained on charging noted. K is then put in the "isolate" position, and the galvanometer brought to rest by means of the short-circuiting key, *k*. The key K is then made to discharge C_2, and the deflection again noted. If there is no leakage, the deflection obtained upon charge and discharge should be equal. The above operations are repeated with the unknown capacity C_1 in circuit. Assuming the battery E.M.F. to have remained constant, the capacities of the two condensers are proportional to the deflections given by them.

COMPARISON BY NEUTRALISATION OF CHARGES.

If two condensers of unequal capacities, having upon them exactly the same quantity of electricity, be connected in series, that is, with the positive of one joined to the negative of the other, and the negative of the latter to the positive of the first, the charges will exactly neutralise: there will be no potential difference between the opposite plates of the condensers; a galvanometer, therefore, connected across either would give no deflection. The E.M.F. which it is necessary to apply to the terminals of a condenser in order to charge it with a given quantity of electricity depends on the capacity of the condenser, as shown by the formula $Q=KV$, where Q is the quantity, K the capacity, and V the potential difference.

If two condensers of unequal capacities be charged with known different potential differences, and if after short-circuiting one on the other, there is no residual charge, the quantities in the two were equal, and we can quite simply calculate the capacity of one condenser from that of the other.

for $K_1 V_1 = Q_1$

and $K_2 V_2 = Q_2$,

but since $Q_1 = Q_2$, $\therefore K_1 V_1 = K_2 V_2$;

$$\therefore K_1 = K_2 \frac{V_2}{V_1}$$

Fig. 287 shows a diagram of the connections. A is a reversing key fitted with ebonite cams so that the moving tongues can be held midway between the top and bottom contacts; B is a charge, isolate, and discharge key; C and D are two condensers, one a known standard, the other unknown; E is the battery; F H is a resistance used as a potentiometer to give varying charges to the condensers by shifting the point of tapping, J; G is a ballistic galvanometer.

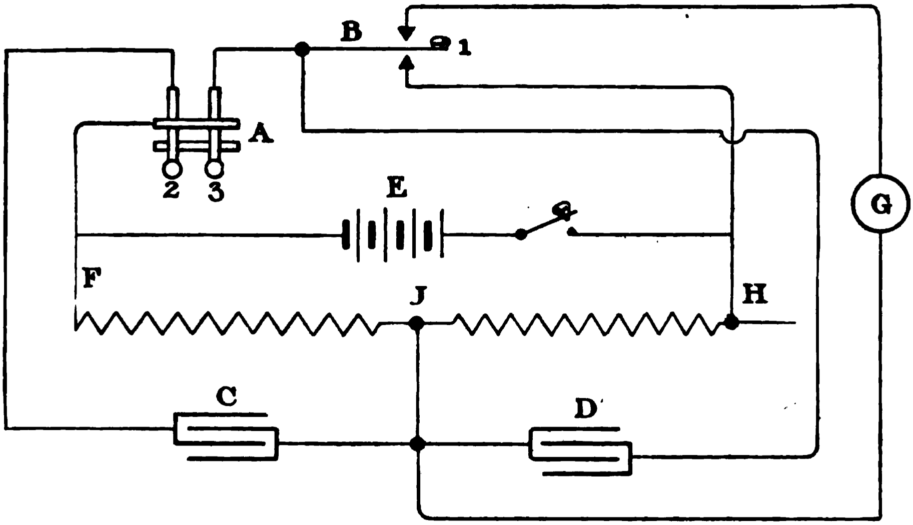


FIG. 287.—COMPARISON OF CONDENSERS BY NEUTRALISATION OF CHARGES.

To begin with, the keys are all in their isolating or midway positions. The operations which have to be then performed are as follows:—

(*a*) Key 2 is allowed to rise to the upper contact, charging the condenser C from the ends of resistance F J. (*b*) Key 1 is depressed, charging the condenser D from the ends of resistance J H. *(c)* Key 1 is put in the isolate position, and Keys 2 and 3 are depressed to touch the lower contact, connecting the + plate of C to the – plate of D, and vice-versa. *(d)* The Key 1 is now raised, and if there is any unneutralised charge left on the condensers, it passes through the galvanometer, producing a kick

The pointing of tapping, J, has to be altered, until after going through the above cycle of operations, there is no deflection upon the galvanometer. The ratio of the E.M.F. applied to the condensers being known from the potentiometer and the capacity of one condenser, that of the other can be calculated as before shown.

MEASUREMENT OF SELF-INDUCTION.

LORD RAYLEIGH'S METHOD OF MEASURING.

In this method, the unknown circuit, the self-induction of which it is required to measure, is connected up as the fourth arm of a Wheatstone bridge. Fig. 288 shows these connections: R_1, R_2, and R_3 are the non-inductive resistance coils of the Wheatstone bridge, R_4 is the inductive circuit, G is a ballistic galvanometer, B is a battery, K_1 is the battery key, K_2 is the galvanometer key.

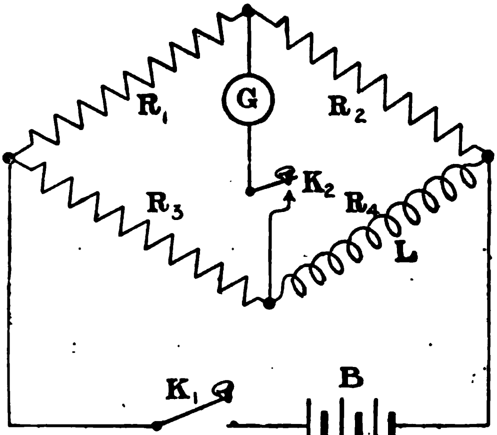


FIG. 288.—RAYLEIGH'S METHOD OF MEASURING L.

Balance is first obtained in the ordinary way, as exactly as possible, first making connection with the battery key, K_1, and then with the galvanometer key, K_2. When this has been carefully done, the galvanometer key is kept closed, and the battery key lifted. This gives rise to a ballistic throw α on the galvanometer due to the E.M.F. of self-induction generated in R_4. The balance of the bridge is not upset by the introduction into R_4 of a small resistance r, which produces a steady deflection, β, on the galvanometer. Both α and β are angular deflections of the needle, *not* scale divisions moved over by the spot.

It can be shown that

$$L = \frac{Tr}{2\pi} \times \frac{2 \sin \frac{d}{2} \left(1 + \frac{\lambda}{2}\right)}{\tan \beta}$$

where T = the periodic time of the needle in seconds, r = the unbalancing resistance in ohms, λ = the logarithmic decrement (*see* page 253), r may be either a small coil, or a straight length of wire, providing that its resistance is known.

SUMPNER'S METHOD OF MEASURING.

This method, which is a fairly satisfactory one, is also based upon the Wheatstone bridge. The connections are shown in Fig. 289.

R_1, R_2, and R_3 are the non-inductive resistance arms, and R_4 is the inductive circuit. R_1 and R_2 should be of high resistance, say 10,000 ohms each. G is a ballistic galvanometer which should also be of about 10,000 ohms resistance. B the battery, and K_1 and K_2 the battery and galvanometer keys respectively. C is a condenser connected across R_1 of about $\frac{1}{3}$ microfarad capacity. The first operation is to obtain accurate balance on the bridge in the ordinary manner. When this has been effected, keeping the galvanometer key closed, the battery key is opened, giving a deflection α, due, as in the preceding method, to the self-induction E.M.F. of R_4. This is repeated with condenser C disconnected, and a second throw, β, obtained. From these data the coefficient L can be calculated from the formula

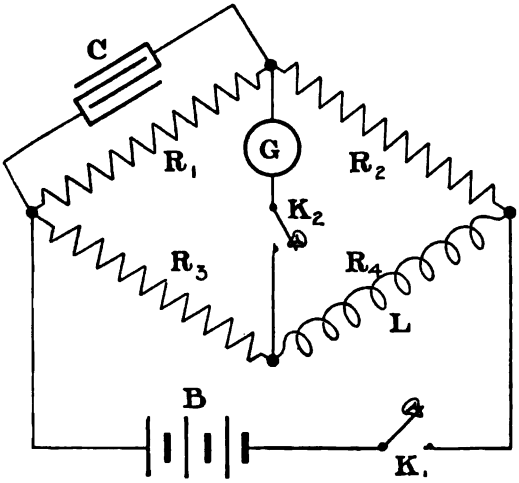


FIG. 289.—SUMPNER'S METHOD OF MEASURING L.

$$L = C R_4 R_1 \frac{\beta}{\beta - \alpha}$$

JOUBERT'S METHOD OF MEASURING L.

The modification of Joubert's method here described is due to Professor S. P. Thompson, and consists in measuring the impedance of the coil or circuit to alternating currents, and also its ohmic resistance. When both these and the frequency of the alternating current are known, the value of L can be simply calculated.

$$\text{The impedance } I = \sqrt{R^2 + 4\pi^2 f^2 L^2}$$

$$\text{And} \therefore L = \frac{\sqrt{I^2 - R^2}}{2\pi f}$$

where f = the frequency in cycles per second. The connections for this method are shown in Fig. 290.

R_1, R_2, and R_3 are the usual non-inductive resistances of the Wheatstone bridge. R_4 is the inductive circuit, whose coefficient of self induction is L. K_2 is a two-way switch, with an "off" position. G is a reflecting galvanometer, not ballistic, and T is a telephone receiver. P and S are the primary and secondary respectively of a small telephone induction coil.

The alternating current of known frequency is furnished by the electro-magnetically operated tuning fork B, which makes a known number of vibrations per second. B_1 and B_2 are batteries.

First, with the galvanometer, G, and the battery B, in circuit, the resistance of R_4 is

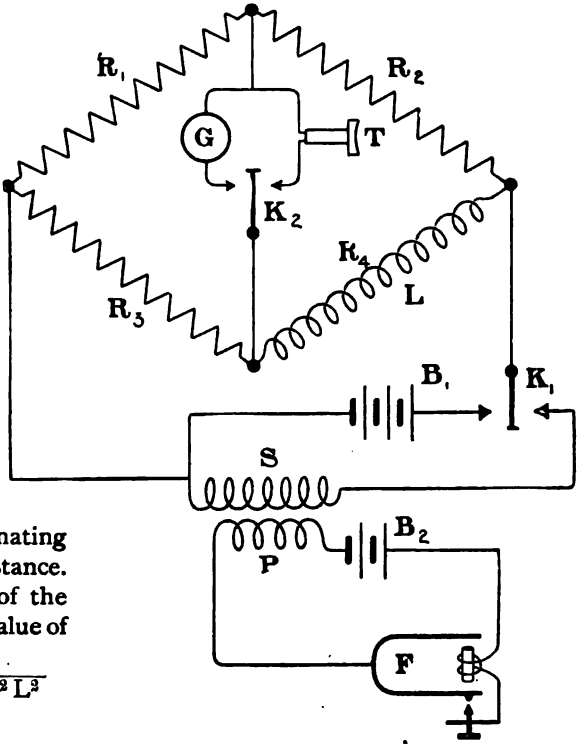


FIG. 290.—S. P. THOMPSON'S METHOD OF MEASURING L.

measured. Then, with the tuning fork vibrating, and the induction coil in circuit, balance is again obtained by means of the telephone receiver, the minimum sound indicating this point.

From the ordinary Wheatstone bridge calculation both R and I can now be calculated, and by combining them in the way shown above, the value of L is at once arrived at.

COMPARISON OF L BY SUMPNER'S METHOD.

Another variation of the Wheatstone bridge is used by Dr. Sumpner to compare the values of L for two coils. The connections are arranged as shown in Fig. 291, R_1 and R_3 being non-inductive resistances, and R_2 and R_4 the inductive circuits. G is a ballistic galvanometer, B the battery, and K_1 and K_2 the keys.

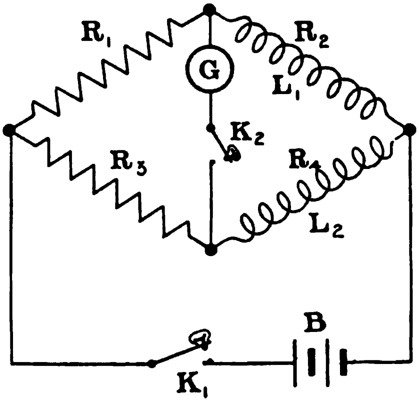


FIG. 291.—SUMPNER'S METHOD OF COMPARING SELF-INDUCTANCES.

Balance is first established in the ordinary way, K_1 being closed first, and K_2 after. After this, K_2 is kept depressed, and K_1 opened, the ballistic swing on G being noted.

One of the inductive coils, say R_4, is now replaced by an exactly equal non-inductive resistance, and the ballistic throw again observed.

If α be the ballistic throw in the first case, and β be the ballistic throw in the second case, then it can be shown that

$$\frac{L_1}{L_2} = \frac{R_1}{R_3} \times \frac{\beta}{\beta - \alpha}$$

WAVE FORM TRACING—JOUBERT'S METHOD.

In 1880 M. Joubert introduced what is known as the contact or point by point method of tracing rapid variations of electrical quantities. Applying it first to the wave of E.M.F. of an alternator, he attached an ebonite disc to the shaft of the alternator, providing it at its centre with a concentric brass disc or drum, and at a point on its periphery with a small piece of metal let into a saw cut made across the edge of the disc. This small piece of metal was connected with the central disc of brass by a wire, and the whole device mounted on the shaft of the alternator. A contact brush was provided to press against the central disc, and another to press upon the edge of the disc. By this means, as the disc rotated with the alternator, contact between the two brushes would only be established at the instant at which the small piece of metal in the edge of the disc was under the upper brush. The two brushes of the ebonite disc formed a portion of a circuit supplied by the alternator and containing a condenser.

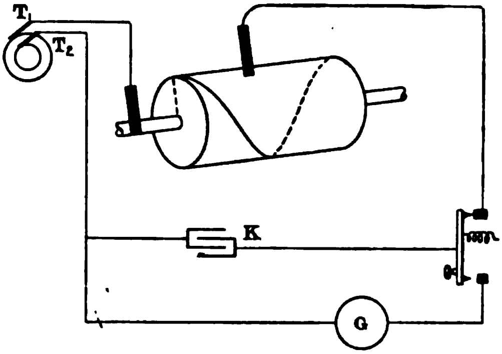


FIG. 292.—PRINCIPLE OF JOUBERT'S METHOD OF WAVE TRACING.

The circuit is shown in Fig. 292, but with a cylinder carrying a spiral strip instead of the disc carrying a piece of metal at its edge as described. The upper brush is capable of adjustment axially along the cylinder and so may be made to make contact with the strip at any instant in the cycle of operations. Thus there is a means of completing the circuit containing the condenser at various instants of time corresponding to various points on the E.M.F. wave, which depend in turn upon the relative position of the field poles and armature coils.

Readings would be taken by the apparatus in the following manner. The alternator would be excited and set in operation and the movable brush set at some fixed position; once during every revolution of the alternator the condenser would be charged to a potential difference determined only by the position of the movable brush. A measurement would then be taken of that potential difference, the only object of the condenser being to provide a sort of receptacle for the potential difference, which should maintain its value without sensible loss, not merely at the instant of the contact, but for so long a time as the brush was not moved and the alternator continued to operate. A reading having been taken thus with the brush in one position, the brush would be adjusted to a new position and a fresh reading taken on the condenser, these operations being continued until a series of points had been obtained connecting the position of the brush with the potential difference of the condenser. The potential difference of the condenser could be read either by an electrometer (*see* page 258) or by means of an electrostatic voltmeter.

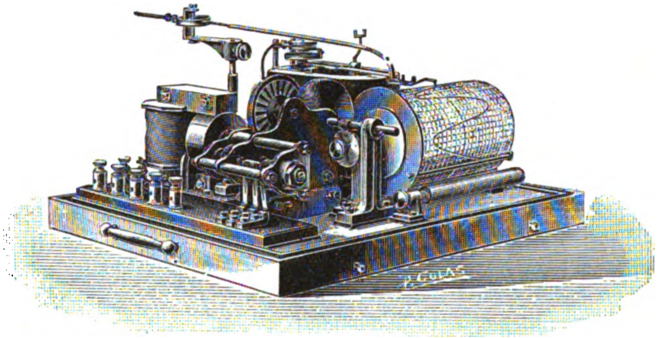


FIG. 293.—HOSPITALIER'S "ONDOGRAPHE."

HOSPITALIER'S "ONDOGRAPHE."

An exceedingly interesting apparatus, which really embodies Joubert's point-to-point method in a neat and compact form has been devised by Mr. E. Hospitalier, and named by him the "Ondographe." The principle of its operation may be explained as follows:—If, in a dark room, a rod be caused to rotate about one end, and have a knob at the other, so that the knob describes a circular path, and the whole be illuminated once every revolution by a flash of light occurring always when it is exactly in the same position, it will appear to stand quite still. If, however, the frequency of the flashes be diminished by a small amount, the rod and knob will have moved a little further on each time before being illuminated, and would then appear to rotate *very slowly* in a forward direction. If the frequency of the flashes were increased, the system would appear to rotate backward. This principle, which is that of the Joubert method, is that made use of in the ondographe. A small synchronous motor is used, which is supplied from the source whose wave form it is required to examine. This motor is connected, through a differential gearing, to a commutator. The differential gearing, is so arranged that when the motor has made a certain number of revolutions, the commutator has made some multiple of this number, *increased or diminished by one.* The commutator first connects the circuit to be examined to a condenser, and then discharges the condenser through a measuring instrument to which is attached a pointer, carrying a pen. The pen moves over a paper strip stretched on a drum which is slowly rotated through reduction gearing by the motor. The measuring instrument, for current and voltage work, is one of the moving coil type. A complete ondographe is shown in Fig. 293. The instrument is not suitable for tracing curves of a non-periodic nature if these cannot be reproduced periodically, and for this purpose an oscillograph is best suited.

OSCILLOGRAPHS.

The oscillograph is an instrument designed to produce deflections in response to varying currents passed through it, the deflections responding so rapidly and so exactly that they are at every instant proportional to the current at that instant. It will be seen that if the instrument is to meet these requirements, the natural period of movement or swing of the deflecting portion must be exceedingly small compared with the time of vibration of the current to be measured. If this is not the case the natural oscillations of the moving portion will come in in such a way as to totally upset a true response in deflection to the current. Secondly, even though the natural period of swing of the moving part be very small, the moving part must not be allowed to vibrate after the current has stopped, and hence some effectual form of damping must be applied. At the same time the damping must not be too great, as it will in that case tend to check the vibrations which are truly in response to the current, so that we see that the damping of the vibrations must only be just sufficient to prevent the deflecting portion as it returns to zero overshooting the mark. When the damping is of this order it is said to be "critical." Thirdly, an essential electrical property of the instrument must be that the current in it responds instantly to the voltage applied at the terminals, since otherwise it will be useless for measurements of variable potential differences. This means to say that the instrument must have an entirely negligible self-induction, and this is desirable not only for the measurement of potential differences, but also for the measurement of currents, in order to avoid disturbing a circuit to be investigated by the introduction into it of the oscillograph. Perhaps the best

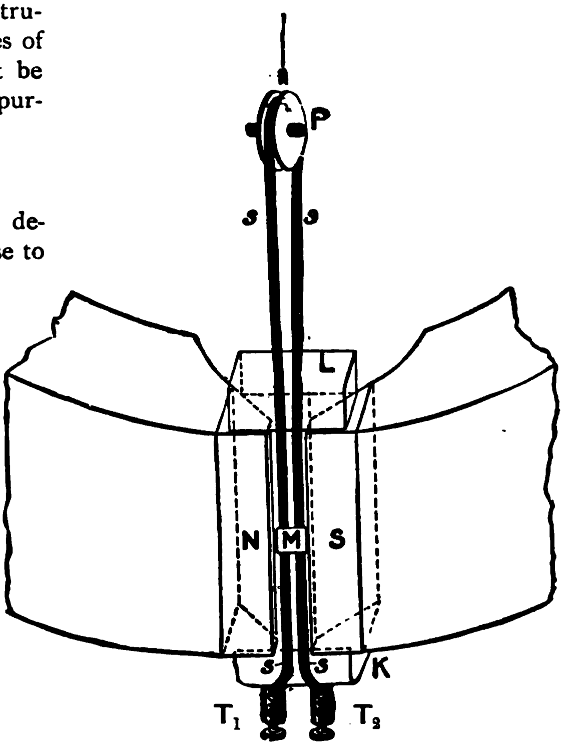


FIG. 294.—DIAGRAM OF MOVING PORTION OF DUDDELL'S OSCILLOGRAPH.

known oscillograph at the present day is that of Mr. W. Duddell. This instrument consists essentially of a D'Arsonval galvanometer in which, however, the field is produced by an electromagnet in order that it may be sufficiently intense, and the coil is replaced by two strips of phosphor bronze which virtually make a one-turn coil. It is obvious that the field must be exceedingly intense since the coil only carries one turn and great sensibility is much to be desired.

Further, in order that the moving system may have an exceedingly high period, the two strips, S S, are not mounted as a coil suspended in the usual manner, but are stretched between two terminals which are seen at T_1 and T_2 in Fig. 294 being formed of one piece of flat phosphor bronze, the loop at the top being kept in tension by being passed over a pulley, P, suspended from a delicate spiral spring. The employment of a pulley renders the tension in the two strips equal, and the tension is readily adjustable by tightening or loosening the spring supporting the pulley. In order that the two portions of the strip which lie in the magnetic field may be parallel to one another, they are passed over a bridge piece L, placed just behind the poles. The poles N, S, of the electromagnet are tapered as seen, in order that the strips may be in as intense a field as possible. In Fig. 295 will be seen three pulleys, the upper one of these three serves to transmit the tension equally to the two lower ones, these two lower ones serving to support two independent pairs of strips, so that the instrument shown is in reality a double oscillograph, the form in which modern instruments are always made. An exceedingly light mirror, as shown at M in Fig. 294, is cemented to the two strips at the centre of the portion which lies in the magnetic field, and since the current must flow in opposite directions in the two strips, they experience forces tending to deflect them in the same direction. The mirror thus becomes rotated through a greater or lesser angle according to the magnitude of the current passing through the strips In the double oscillograph there are three mirrors, those on either side of the central one being attached to strips in the same way as is shown in Fig. 294.

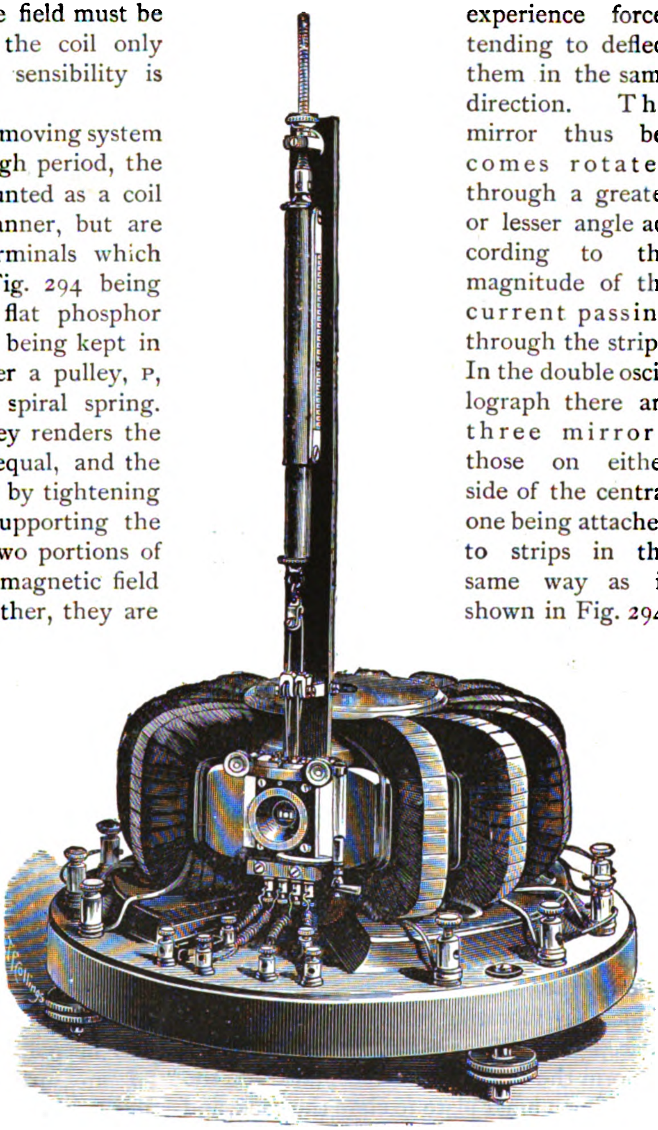


FIG. 295.—DUDDELL'S COMPLETE OSCILLOGRAPH.

The strips depending from the pair of lower pulleys lie in two separate gaps so as to be quite independent of one another and between the two gaps is a fixed iron magnetic bridge piece which carries a central fixed mirror. The object of this central mirror is to provide a fixed spot of light as a reference for zero, the two working mirrors serving simultaneously to indicate variations of voltage and current. Now, it will be clear that if light is thrown on to the working mirrors and the strips be supplied with current of an alternating character, one strip receiving a current proportional at every instant to the voltage of the circuit and the other a current proportional to the current in the circuit to be investigated, they will merely oscillate to and fro, and if the spots be received on a scale in the usual manner they will merely be, if the oscillations are sufficiently rapid, two white streaks of light thrown on the scale. If, however, instead of looking directly at the scale, use is made of a rotating mirror similar to that with which Foucault measured the velocity of light, the axis of the mirror being placed parallel to the line of light formed by the travelling spots, the spots will appear, not as straight lines, but as wavy lines of light. Further, if the conditions laid down for the true performance of an oscillograph are fulfilled, these waves of light will truly represent the time variations of the voltage and current of the circuit to which they are connected. It is, of course, essential that the speed of the mirror shall remain to all intents and purposes constant, in order that true representations of the wave forms may be obtained. In order to provide the damping to which reference has been made, Mr. Duddell fills the space in which the vibrating portion of the strips is placed with oil, employing the pole pieces to form the sides of the receptacle for the oil, using a brass plate to close the back, and a lens-shaped glass front to complete it. An exceedingly interesting and ingenious device is resorted to in this connection. The viscosity of oil depends, as is well known, upon its temperature, and hence in order to obtain the correct amount of damping an oil is used which is too viscous at ordinary temperatures and its temperature is raised until the viscosity has decreased to precisely the amount required for critical damping. This is readily tested by applying sudden deflecting forces to the oscillograph and noting whether there is any oscillation at the end of a deflection either on the sudden application or on the sudden removal of the deflecting forces.

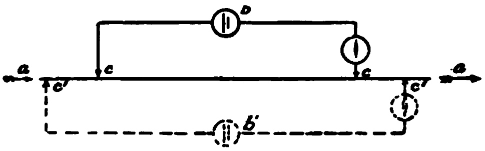


FIG. 296.—PRINCIPLE OF POTENTIOMETER.

THE POTENTIOMETER.

A method of measuring E.M.F., current, and resistance, which has been greatly developed of recent years by various workers, is the potentiometer method. As this method is used for measuring each of these three the description of it has been left until the ordinary methods of measuring each property had been dealt with.

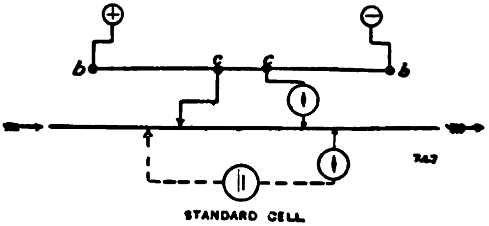


FIG. 297.—METHOD OF MEASURING CURRENT BY POTENTIOMETER.

Owing to its ease, accuracy, and rapidity of manipulation, the portability of its various forms, and the few auxiliary instruments required, the potentiometer is extensively used in works and central station testing.

The universal applicability of potentiometer methods will best be explained by reference to some particular form of the instrument, such, for example, as the well-known Crompton form. In potentiometer methods all measurements are reduced to the comparison of voltages, a very high degree of accuracy being obtained by employing the fall of potential down a number of accurately adjusted equal resistances placed in series with one another, the resistances being also in series with a very carefully constructed slide wire.

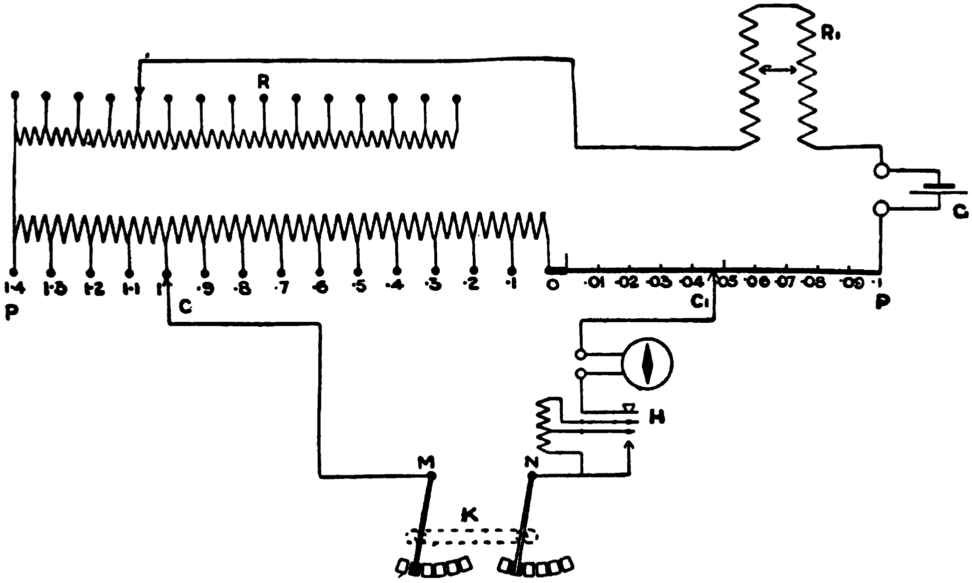


FIG. 298.—POTENTIOMETER CIRCUITS.

The slide wire is accurately adjusted, and the resistances of its various lengths are indicated on a scale in terms of the value of one of the equal resistances in series with it. The principle of the potentiometer is shown in Fig. 296. A current passes along the wire *a a*. The cell *b*, with a galvanometer in series with it, is connected by means of two sliding contacts c c to the wire *a a*, the E.M.F. of the cell being in opposition to the E.M.F. due to the fall of potential in the wire. The distance of the contacts from one another is then adjusted until the galvanometer shows no deflection, showing that the E.M.F. of the cell is equal to the drop along *c c*. It will be noted that it is the true internal E.M.F. which is measured, since the cell is delivering no current. If the cell is replaced by another and the sliding contacts are readjusted to the position *c′ c′*, then the lengths *c c* and *c′c′* are in the same ratio as the internal E.M.F.'s of the two cells, provided that the current in the wire *a a* has not changed and that the resistance of the wire does not vary with temperature.

Now it is convenient to have a cell as a standard of reference, but we wish to measure differences of potential varying from nothing up to hundreds of volts, and, for values greater than the E.M.F. of the standard, such voltages are applied to the ends of a resistance which is accurately subdivided so that known fractions of the applied voltage can be tapped off and balanced against the standard or a fraction of it.

Fig. 297 shows this method, *b b* being the resistance and *c c* a known fraction, say one-hundredth or one-thousandth of it. The instrument which contains the resistance *b b* with its subdivisions, is called a volt box. If currents have to be measured they are passed through a standard resistance, various closely adjusted standards being supplied with the potentiometer; the fall of potential down such resistances is an accurate measure of the current traversing them, and is determined by being balanced against a known fall in the potentiometer wire. Resistances are measured by passing a current through them and comparing the voltage (fall of potential) across them, with the voltage across one of the standards connected in series with the ones to be measured.

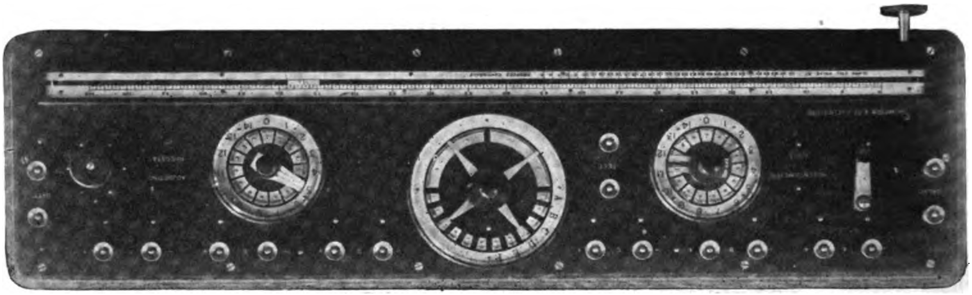


FIG. 299.—CROMPTON POTENTIOMETER.

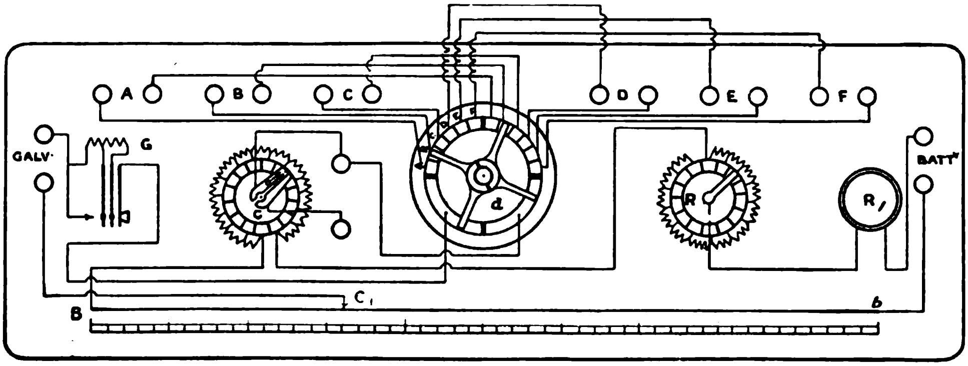


FIG. 300.—CIRCUIT DIAGRAM OF CROMPTON POTENTIOMETER.

For measurements of voltage and current, the procedure is as follows: A Clark cell, the E.M.F. of which is, say, 1·4345 at the temperature of the test room at the time, is used as a standard of E.M.F., and current is sent through the fourteen equal resistance coils and through the slide wire, the current being then carefully adjusted until the fall down the fourteen coils *plus*

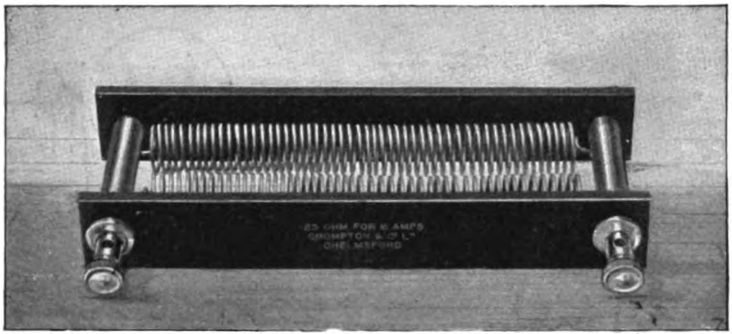


FIG. 301.—STANDARD 0·1 OHM RESISTANCE TO CARRY 5 AMPERES.

that down 0·345 of the length of slide wire exactly balances against the E.M.F. of the standard cell. Under these conditions the fall down each coil and down the whole slide wire is 0·1 volt. The slide wire is subdivided to hundredths of its length, and thus the length between any two marks has a fall of 0·001 volt. The connections are shown in Fig. 298, where P P is the potentiometer wire proper consisting of coils marked 0·1, 0·2, etc., to 1·4, and the slide wire marked 0·01 to 0·1. The movable tapping points are marked C, C_1. In the upper part of the diagram is shown the adjusting resistance by which the current in the potentiometer wire is varied. The battery G supplies this current, and by means of the coils R and rheostat R R_1, the current is adjusted as above described, so that the voltage across each potential coil is 0·1 volt. The actual construction of the instrument is shown in Fig. 299.

One sliding contact, or tapping point, C, may be moved over the terminals of the potentiometer coils step by step, and the other, C_1, along the wire. The switch in-

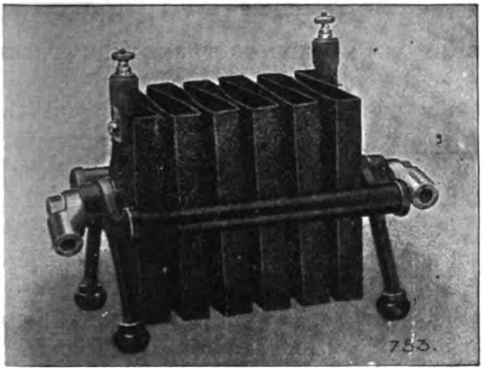


FIG. 302.—STANDARD 0·001 OHM RESISTANCE TO CARRY 500 AMPERES.

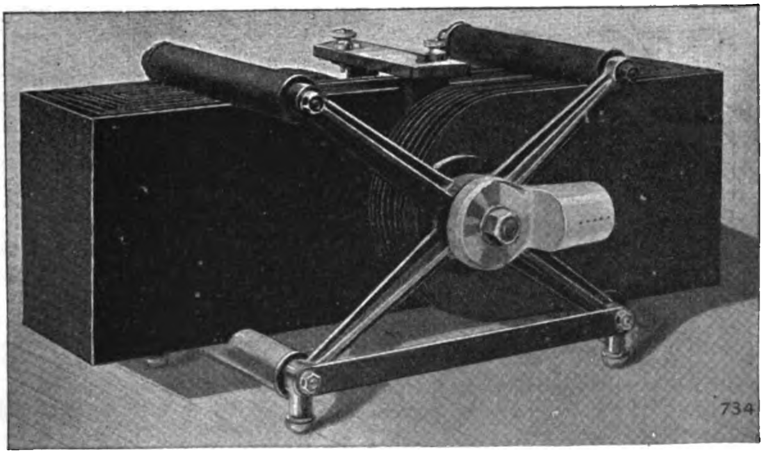


FIG. 303.—STANDARD 0·001 OHM RESISTANCE TO CARRY 1,000 AMPERES.

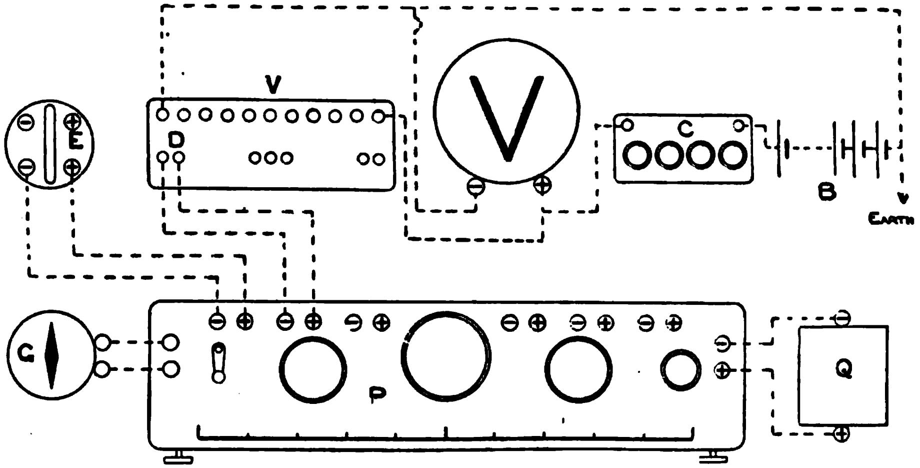


FIG. 304.—CONNECTIONS FOR TESTING VOLTMETER ON ONE SIDE OF THREE-WIRE SYSTEM.

dicated at *d* in Fig. 300, has its contacts connected to the pairs of terminals A, B, C, D, E and F, so that a voltage applied to any one of these pairs may at once be balanced against a portion of the fall down the potentiometer, by putting this switch in the appropriate position. In ordinary work the tapping points are first set at the correct position to correspond with the E.M.F. of the standard cell, and current through the coils and slide wire is carefully adjusted by the switch and the rheostat R, until the galvanometer gives no deflection. The figures on the coils and slide wire now indicate the fall of potential direct in tenths and hundredths of a volt as explained above. For calibrating voltmeters the method shown in Fig. 304 is employed with the additional aid of a "volt box." Volt boxes are made in several different sizes, depending on the maximum voltage required to be measured.

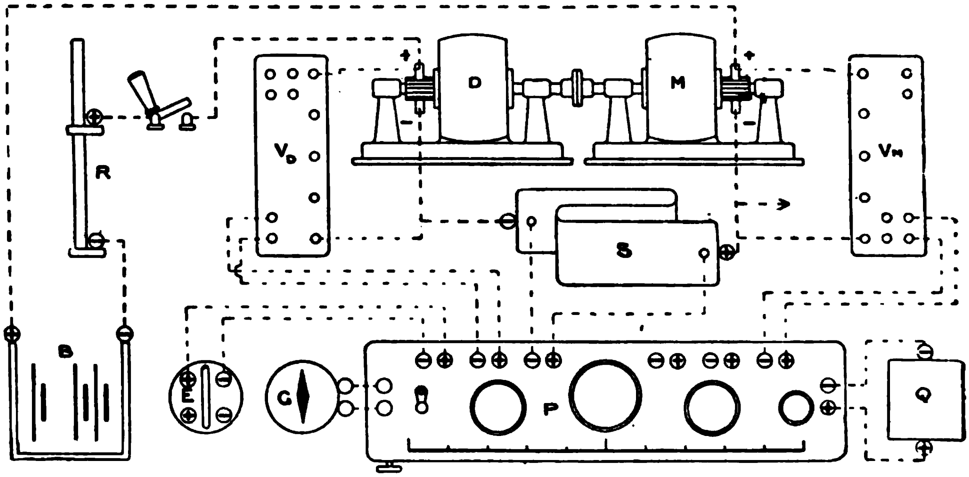


FIG. 305.—APPLICATION OF POTENTIOMETER TO HOPKINSON TEST.

They are merely boxes containing resistances and considerable numbers of terminals so arranged that whatever be the voltage of supply, the voltage of the tapping to supply the potentiometer is between one and two volts. The voltmeter and a source of variable voltage are connected to the high value terminals of the volt box, and the terminals giving one-tenth or one-hundredth (or other decimal fraction for still higher pressures) of this value are connected to one pair of testing terminals on the potentiometer.

The terminals marked "test" in Fig. 299 are connected to the two arms of the switch—and so enable each coil of the set of fourteen to be tested separately if its accuracy be doubted.

The resistances used with the potentiometer for measuring currents consist of open spirals or broad metal strips large enough to carry the current for which they are rated with a rise of temperature of about 30° C. They are made of aged and selected manganin, and with this degree of heating their values remain practically unaltered.

Fig. 301 shows a resistance of open spirals of round wire to carry 5 amperes. Figs. 302 and 303 are resistances of flat strips to measure up to 50 and 2,000 amperes respectively.

Fig. 305 shows the method of using the potentiometer to measure the efficiency of two similar machines. The machines D and M are started up by an auxiliary machine or battery, connected through a variable resistance R, and the standard resistance S, so that M runs as a motor and D as a generator. The terminals of the machines are connected to the volt boxes, and the tappings from these along with the leads from S, and the Clark cell E, are connected to the potentiometer. The readings of S and V_M give the power supplied to the motor, and those of S and V_D the power returned by the generator.

SECTION VI.

ALTERNATING CURRENTS.

CHAPTER I.—PROPERTIES OF UNSTEADY CURRENTS.

THE EFFECTS OF UNSTEADY CURRENTS—COEFFICIENT OF SELF-INDUCTION—ALTERNATING CURRENTS—POWER IN ALTERNATING CIRCUIT.

THE magnetic effect of a current flowing in a conductor is capable, under suitable conditions, of reacting upon the conductor in a manner which produces results that are very startling at first sight. The suitable condition for the production of this reactive effect is that the current shall not be a steady one, and this condition may be obtained in several ways. If we consider what happens in a coil of wire when the current in it is changed in any way—for instance, when the current is made to grow steadily from nothing up to a fixed value—we see, in the first place, that the magnetic flux produced by that current will also grow from nothing up to a fixed value. If there be no iron in the magnetic circuit, then the flux will, at every instant, be strictly proportional to the current in the coil. In the second place, we see that if, when the current has reached its final value, there are magnetic lines in the coil, and there were none to begin with, or even if there were some, but a different number, then we have effected a change in the number of lines threading the coil, and, according to what we have seen in Section IV., there must consequently have been some cutting of lines of force by the coil and a resulting E.M.F. Without stopping here to consider how the cutting actually arises, let us investigate what the direction of the E.M.F. will be as compared with the current. Lenz's law (Section IV., Chapter IV.) shows us that the introduction of a field into a coil tends to generate an E.M.F. of such a kind as will produce a current to oppose the introduced field. Now, in the present case, we have a current which has grown, and which in its growth has, in effect, introduced lines of force into, and in a certain direction through, the coil; the introduction of these lines must therefore set up an E.M.F. of a kind to produce a current which would oppose these lines, and therefore in the opposite direction to the current which is being forced through the coil. This E.M.F. is thus also in opposition to current flowing, and since it has been induced in the coil by the action of the current itself (through the medium of the field) it is called the back E.M.F. of self-induction. The self-induced E.M.F. plays a most important part in all circuits where the current is frequently changed, either in a circuit in which the current is stopped and started frequently or in a circuit in which the current is continually changing. Circuits in which the current is continually changing are in common use, the currents being called *alternating currents*. Before looking into the peculiar properties of alternating current circuits it behoves us to study self-induction a little more closely.

It is important for the student to realise first that self-induction can only be in operation when a current is changing, and next that when the current is changing self-induction must always be operative. Certain circuits, it is true, are spoken of as having no self-induction, or as being "non-inductive," but, as we shall see, it is not that there are no such forces at work, it is simply that the forces at work are all so arranged as to balance one another almost perfectly, so that the ultimate self-induction is negligibly small. Let us examine now a few cases of changing currents, with a view to seeing exactly how each will be affected by self-induction.

One of the very commonest cases of a changing current is that of the electric bell. The ordinary trembling bell automatically stops the current every time the hammer is attracted to the gong, and then when the hammer flies back the current is started again, only to be again broken just as the hammer approaches the gong. Here, then, is a case of a circuit in which the current is continually being started and stopped, and from what has just been said we should expect to find in this circuit the effects of self-induction. As a matter of fact, we do find them; without them the bell would not work at all, and they usually show themselves in a very familiar effect. So soon as the spring contact leaves the fixed contact, and the current in the coils dies out, the magnetism also dies down. The magnetism is, of course, fairly powerful, and the coils of wire contain a considerable number of turns; the whole magnetic flux in dying down may be regarded as cutting the whole of the turns, and since the dying away of the field occurs very rapidly we have all the necessary factors for a big E.M.F. It will be remembered that the induced E.M.F. is proportional to the *rate of cutting*, and hence the number of turns in the coil, the magnitude of the magnetic flux which dies away, *and the rapidity with which it dies* all influence the magnitude of the generated E.M.F. In the present case there is a very considerable product from these three factors; indeed, it is so great that when the two contacts are just separating the weakening of the field is so rapid that the self-induced E.M.F. becomes large enough to make the current jump across the air gap between the two contacts, and we see the resulting spark. We shall find that whenever a circuit is broken and a spark produced, the spark is the result of the high E.M.F. generated by the falling off of the magnetic field. It is now left for us to consider what will be the effect of self-induction on the coil when the current in it is started. The current is started by the closing of the contacts, and this means that the full E.M.F. of the battery is at once put to work on the coils. The current, however, does not at once attain the value $\frac{E}{R}$, but rises gradually to this value, so that the backward swing of the hammer is not checked so soon as it otherwise would be (*see* page 218). We are so accustomed to finding a bell respond instantly to the pressing of the bell-push that it is only natural to find it commonly believed that the current instantly rises to its full value. Not only is this idea supported by the common experience with bells, but those who use much heavier currents in engineering work are so accustomed to seeing their instruments respond apparently instantly to the switching on of currents, that they, too, apart from their knowledge, would assume that the current instantly rises to its full value. That this cannot be the case in a circuit containing any magnetic apparatus whatever, is obvious, for when the switch is closed, and the current begins to rise, the magnetism in the apparatus begins to rise, too, and the growing of this field must of necessity set up a back E.M.F. of self-induction, opposing the current producing the field, with the result that the growth of the current is retarded. In most circuits in common use the time taken by the current to grow from nothing to its maximum value, when a steady E.M.F. is suddenly applied, is, indeed, small—it may well be so small as the one-hundredth of a second—so that it is no wonder in such cases that the current is regarded as growing instantly to its full value. In many circuits, however, the effect of self-induction is much greater, and we may easily find the current taking as much as half a second to grow to its full value, whereas a circuit specially designed to have a high self-induction may cause the current to take as much as one to two hundred seconds to grow to its full value. By "full value" is meant a value not appreciably less than $\frac{E}{R}$. To take the case of a certain very ordinary 20 kilowatt bipolar shunt generator, if 80 volts were suddenly applied to the terminals of the shunt winding, the shunt current would take 15·7 seconds to reach 99 per cent. of its $\frac{E}{R}$ value.

The whole effect of self-induction may usefully and accurately be likened to the effect of *mass inertia* in mechanics, self-induction in electricity giving to the current an apparent mass. In the study of mechanics we find that whenever a body has its motion changed—that is, when it is started or when it is stopped, when it is accelerated or when it is retarded—we find a force at work opposing the change, a force, moreover, which comes into operation only so long as a change lasts. When a single railway truck has to be moved without the assistance of steam, the men pushing it know well enough that nearly all the labour is connected with getting the truck into motion, and that if the track be level so soon as the truck has reached the required speed, very much less effort is necessary to keep it going than was necessary at the start to set it in motion. The men, in other words, had to do a great deal of work in starting the truck, and, having started it, have very little to do in maintaining the motion. The maintenance of the motion only involves the overcoming of friction, whereas the getting into motion involved overcoming the inertia of the truck. The same remarks will, of course, apply if, when the truck has reached one speed, it is desired to increase the speed to a higher value; or if the change to be produced is of the opposite kind, that is, if the truck is to be deprived of its speed, everybody knows that forces due to the inertia of the truck will again come into play. If the truck is to be stopped without the use of brakes (which very much mask the effect of inertia), great force will have to be exerted against the truck, whose inertia opposes this change, and it is very well known that the more rapid the change the greater the force necessary; in other words, the more suddenly the truck has to be stopped the greater the force necessary. As the men have to push against the motion of the truck to stop it, the truck may be considered as pushing them, since they are forced to step backwards, and hence the truck can properly be regarded as doing work on the men, for it is doing precisely to the men what they did to it when they started it.* The truck thus gives out work, and if it be asked where the truck got the work from, the answer is, the men put the work into it when they started it into motion, and that work, the work done in starting, was stored up in the truck by virtue of its motion so long as its motion continued. In losing its motion the truck did but give out again what it had been given, and what it retained by virtue of its motion. These facts have been dealt with in such detail because they very fully illustrate the facts of self-induction.

---

* That is, it is pushing them against the opposing force which they exert, and hence is delivering energy to them. Of course they, on receiving it, do not to any marked degree *store* it as the truck did, but dissipate most of it in several directions.

The starting of a current in a circuit possessing self-induction involves the starting of a magnetic field, which, as it starts, cuts the conductors of the circuit, reacting upon them and producing a force opposing the start. When the current has reached a steady value the magnetism remains steady, and all that has to be done to keep the current going is to overcome the resistance of the circuit. If, now, the current has to be stopped, the magnetic field dies away, cutting the circuit in the opposite sense, reacting upon it to produce an E.M.F. opposing the stoppage of the current. In so doing, the E.M.F. of self-induction, by tending to maintain the current, does work upon the circuit. The magnetic flux, by virtue of its reactive effect on the coil producing it, represents a definite amount of work done, and the need of this work is felt in the circuit by the current having to be forced against the opposing force of self-induction, and the magnetic field, in dying away, does but restore to the circuit the energy that had been stored in it, this energy appearing as the self-induced E.M.F. maintaining the current, when the original force producing the current had been partially or entirely removed. All the time the magnetic flux was not changed it neither involved an expenditure nor a return of energy, the only energy required being that necessary to overcome the resistance of the conductors, a thing quite independent of the field. The effect of the self-induction upon a circuit to which a steady E.M.F. is applied is embodied in what is known as Helmholtz's law, which may be written as follows:

$$C_t = \frac{E}{R}\left(1 - e^{-\frac{R}{L}t}\right)$$

Here C_t is the current strength t seconds from the instant of application of E, while E and R have their usual meaning, the quantity e being the base of napierian logarithms, and L a quantity to be described presently and known as the co-efficient of self-induction of the circuit.

If a curve having the above equation be plotted we obtain that given in Fig. 306.

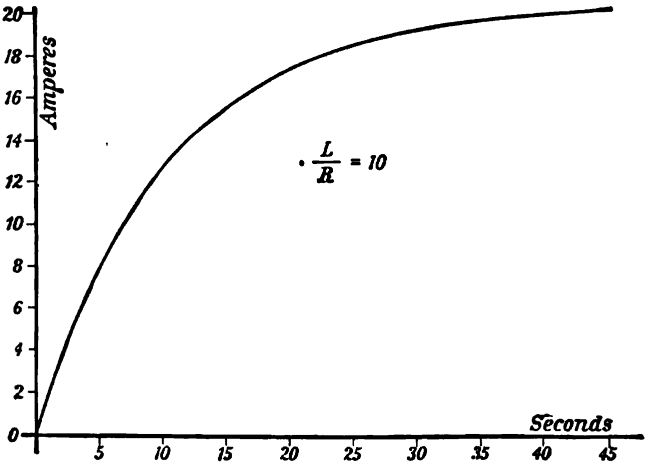


FIG. 306.

The quantity $\frac{L}{R}$ is called the "time constant" of the circuit, and if we examine it we come to the extraordinary conclusion that if it were not for resistance a current in any inductive circuit would take an infinite time to grow to a definite percentage of its final value, that is, it would grow infinitely slowly, and further, that in a circuit of given self-induction, increasing the resistance will enable the current to grow more rapidly to its final value, though the final value will, of course, be proportionately less. Resistance, therefore, comes to us in this connection in the guise of a friend, and, indeed, the common attitude of beginners towards electrical resistance in regarding it as an unmitigated evil is as unjustifiable as the corresponding attitude to mechanical friction. Just as we find friction is indispensable in mechanics in enabling a screw or a nail to hold, or a man to walk, so also resistance in electrics is indispensable in allowing current to be turned to a useful purpose.

The numerical value of $\frac{L}{R}$ when L is in henrys and R in ohms, gives the time in seconds taken by the current to reach the value :

$$\frac{E}{R}\left(1 - \frac{1}{e}\right) \text{ or } 0{\cdot}634\,\frac{E}{R}$$

CO-EFFICIENT OF SELF-INDUCTION.

The quantity L, called the co-efficient of self-induction, represents the capability of a circuit to produce inductive effects just as the letter R is used to represent its resistance: that is, its capability to hinder the flow of a currrent. Resistance is measured in terms of a definite unit, and it also becomes necessary to obtain a unit in terms of which the self-inductive property of a circuit can be measured. Now, the inductive effect in a circuit depends upon the rate of cutting of lines of force by the conductors and upon nothing else, but since the rate of cutting will depend upon two things, namely, the rate of change of the magnetic flux and the number of conductors composing the circuit, embracing the flux, we can investigate the self-inductive property of a circuit by considering these two quantities. If we assume that every line threads all the conductors, the number of conductors to be cut by the flux is a very simple quantity, and requires no further consideration. The rate of change of magnetic flux involves, however, two things, one being the total range of the change and the other the speed with which that range is passed through; we may, for example, change a matter of 2,000 lines in 200 seconds, getting a rate of 10 lines per second, or we may get a total change of only 100 lines, which, if it occur in half a second, will mean a rate of change of 200 lines per second, giving an induced E.M.F. 20 times as great as that which the former rate of change would have given. The changing magnetism that we are considering is a magnetic flux produced by the current, and we may hence transfer our attention from the flux to the current, since a rapidly changing current will mean a rapidly changing flux, and a slowly changing current will mean a slowly changing flux.

To fix our ideas, let us consider how the production of a given flux may be effected. We will take a non-magnetic tube, such as glass or brass, and produce in it a flux of given strength. This may be done by winding the tube with wire of any thickness, the only necessity laid upon us being the production of a given number of ampere-turns. Let us provide these ampere-turns first in one way and then in another. If the number required be 250, let us provide in the first case 10 turns of wire carrying 25 amperes, and in the second case 100 turns of wire carrying 2½ amperes. If we compare the relative self-inductive values of these circuits by supposing the current to change at the same rate in each, say, at the rate of half an ampere per second, then if the current is getting less uniform at that rate it will take 50 seconds to die down to nothing in the first case and 5 seconds in the second case. In the first case, then, we shall have the flux of, say, N lines, cutting 10 turns of wire in 50 seconds, and the total rate of cutting will be $\frac{10 \times N}{50}$ lines cut per second. In the other coil, we shall have $\frac{100 \times N}{5}$ lines cut per second, that is a rate of change in the second case 100 times as great as that obtained in the first case. It must be clearly noted that we have in each case used exactly the same flux produced by exactly the same number of ampere-turns, the only difference in the two circuits being the number of turns of wire composing them. The numbers given above would lead us to suppose the rate of cutting to be proportional to the square of the number of turns, provided the rate of change of the current and the total flux produced remained constant. This supposition is easily shown to be correct by proceeding to discuss, in a general way, mathematically, the particular case given above.

We might proceed on these lines to define the self-inductive property of a circuit and to lay down the magnitude of a unit in terms of which that property may be expressed. This has been done, a circuit being said to have the unit of self-inductive property if the back E.M.F. of self-induction in it is one volt when the current in it is changed *at the rate of* 1 *ampere per second*. This is otherwise expressed by saying that when these conditions hold, the coefficient of self-induction of the circuit is one unit, and the name "henry" has been given to the unit in honour of the American electrician, Henry. Hence, if a circuit is said to have a self-induction coefficient of 3 henrys, what is meant is, that if the current in it be changed at the rate of 1 ampere per second, there will be 3 volts back E.M.F. of self-induction. If the tube above referred to were 2 inches long and about 5⅝ inches in diameter, the fine wire winding would give a coefficient of about 0·02 henry, and the thick winding about 0·0002. The henry is a somewhat inconveniently large unit, the coefficients which have most commonly to be dealt with being of the order of one-hundredth of a henry. On the other hand, the henry is a most convenient unit, because it has been laid down on such excellent lines, all the quantities in it being, as will be noted, of unit magnitude in the scale of the practical units. If therefore, we know the coefficient of self-induction, L, of a circuit, we have only to multiply this by the rate of change of current to obtain the magnitude of the back E.M.F. in volts.

In the case discussed above, the conditions were about as simple as it is possible to have them. If, however, the coil had been wound on iron or steel instead of on a non-magnetic material, matters would have been more complex.

In the example given it was assumed (1) that the current, and (2) hence, the lines of force, died away at a uniform rate throughout the whole period of that operation. The second assumption was correct in view of the fact that the coils were wound on glass or wood, or some non-magnetic and non-conducting material. If, however, the core be of magnetic material such as iron, steel, or even nickel, the rate of dying of the flux will not correspond precisely with the rate of dying of the current, but will depend upon the degree of magnetisation that has been attained at the maximum, and upon the precise nature of the magnetic core. In other words, the flux produced is not proportional to the current, but follows a very irregular law. This has been pointed out in Section IV., and the curve of magnetisation of iron is again given here in Fig. 307. An examination of this curve makes it at once evident that if the current change in a given time so as to reduce the magnetomotive force down any one of the three equal steps marked M_1, M_2, M_3 on the diagram, that such diminutions of the magnetomotive force would be accompanied by unequal diminutions of the magnetic flux; hence, if the three changes are made in equal times, and in each case there is therefore the same rate of change of current, there is not the same rate of cutting of lines in the three cases. The rate of cutting of lines, however, is what determines L for this circuit, and hence we see that L is not a fixed quantity for the circuit in question, and the deviation from constancy is due to the variation in the magnetic permeability of iron. This change in the coefficient of self-induction is of very great importance when the degree of magnetisation of the core is pushed above the knee of the curve; but we see, too, that when it is pushed above that point, the value of L remains sensibly constant for any further degree of magnetisation, since the curve of magnetisation above that point is virtually a straight line. The portion, too, lying below the knee is approximately straight for a considerable distance. The accompanying curve, Fig. 308, illustrates the changes in the value of L for a coil of 100 turns wound on a closed cast steel core 0·8 in. in diameter, and having a total length of 10 ins., the abscissæ giving the excitation for this particular coil.

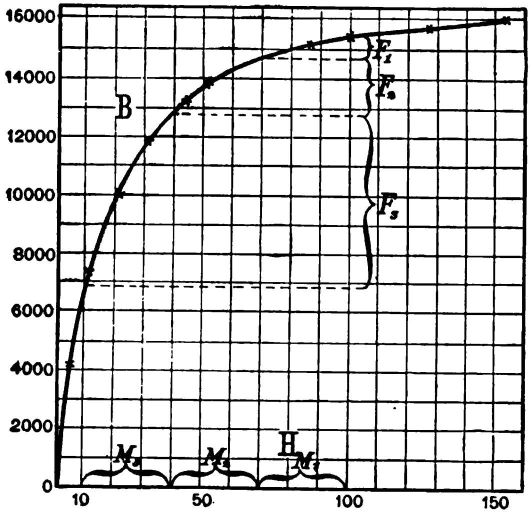


FIG. 307.

ALTERNATING CURRENTS.

Most people are nowadays familiar with the fact that some electrical supply companies provide their customers with what is called a direct or a continuous current, while others supply what is called an alternating current. The continuous current, as is well known, is of precisely the same character as the current that one obtains from a battery, but the properties of an alternating current are not so commonly understood. The main property of an alternating current, as the name implies, is that it periodically reverses its direction. Perhaps the easiest way to convey an accurate idea of an alternating current is to liken it to water in a pipe pumped to and fro by an oscillating piston as shown in Fig. 309. The piston oscillates to and fro in the cylinder from end to end, reversing its direction each time it reaches the end of a stroke, and we may consider the electricity in an alternating current circuit to oscillate round the circuit just as the water in the analogue is caused to oscillate round the pipe circuit. In the figure the piston is supposed to be driven by a crank, and the pipe and both ends of the cylinder to be quite full of water. The crank must be supposed to revolve at a uniform speed, and it will at once be seen that the motion of the piston in the cylinder is continually

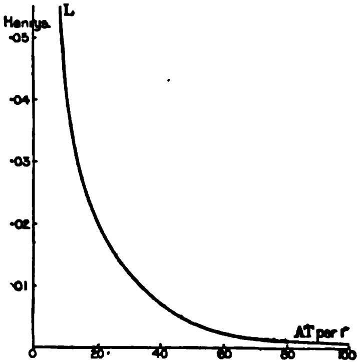


FIG. 308.

changing; in fact, its motion is precisely the same as the motion of a pendulum or swing.*

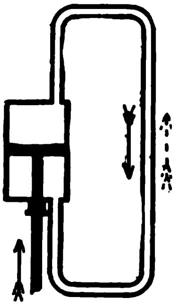


FIG. 309.

Now every child knows when it is in a swing that, commencing from the top, when the swing is just about to descend, the motion, beginning at nothing, gets faster and faster until it reaches its maximum speed as it passes between the posts, and the speed then falls off until the highest point is reached on the opposite side. So with this piston. The fly wheel driving it is supposed to rotate at a perfectly steady rate, but the piston will have a *speed* which depends upon its *position*, its speed being greatest in the middle of the stroke, and continually changing from that greatest value down to nothing as it reaches the end of a stroke, and then from nothing up to the maximum as it returns to the middle position. This simple matter has been spoken of because it describes a series of operations which is of great importance. The important point about it is that the speed of the piston is always changing. We want to know exactly how it changes. If we are to plot a curve to show how that speed changes we must proceed first to study the connection between position and time as follows: Let us draw a semicircle on a vertical diameter (Fig. 310) to represent the path of the crank pin through half a revolution, and then, if we neglect the very slight error due to the connecting rod being short, we can get the motion of the piston in the following way: From the centre of the semicircle draw a line at right angles to the diameter for time measurements. Now mark off a number of equidistant points on the circumference of the semicircle, and along the horizontal line mark off a number of points which must also be equidistant from one another, but whose distance from one another need have no particular relation to the distance between the points on the semicircle, since it merely represents some interval of time. Now let us suppose the piston to be at the middle of its stroke and moving up; the crank will then be lying horizontal, and the end of it, therefore, will be at the point marked 0 on the semicircle. If the crank revolve clockwise it will reach points 1, 2, 3, 4, etc., in succession, and the time taken to pass from any one point to the next will always be the same. The points along the horizontal axis of reference are taken to represent the lapse of time, and if the crank take 32 seconds to complete one revolution, it will take two seconds to pass from point 0 to point 1 on the circle; the distance from 0 to 1 on the horizontal line may then be used to represent two seconds and so on. Now for the position of the the piston. When the crank pin has moved from 0 to 1 the piston will have been raised vertically by the amount by which the crank pin has risen (always neglecting the angularity of the connecting rod). If we started making our observations precisely at noon, the crank-pin would have been at 0 at noon, and the piston in the middle of its stroke, and at two seconds past noon (this instant of time is repre-

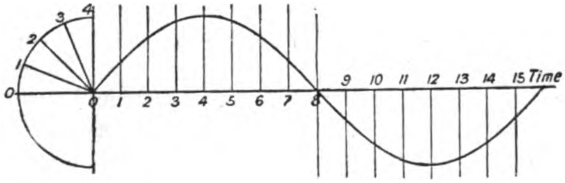


FIG. 310.

---

* That is, neglecting the angularity of the connecting rod. The motion is not a simple harmonic motion, unless the connecting rod is infinitely long.

sented by the point 1 on the horizontal line) the piston will have risen through a distance shown by projecting the horizontal line from the crank pin. This may be projected far enough to come over the point 1 on the time axis, and this will give us a point representing by its distance above the horizontal line the position of the piston above its middle point, and by its distance from the diameter of the semicircle the time that has elapsed since noon. We proceed to find the other points in exactly the same way. When the crank pin has reached the point 2 the projecting line will show the height through which the piston has been raised, and the point where this projecting line meets a vertical line through the point representing four seconds past noon will be the next point on our curve. Of course, when the crank has reached the vertical position, its downward passage to the right hand of the diameter will be exactly the same as the return movement through the points 7, 6, 5, and so on, and we get the complete curve shown in Fig. 310. It must be clearly understood that any point on this curve represents the connection between two things, namely, the distance of the piston from its mid position and the instant of time when it is there.

This apparently simple matter has been described at this length in order that those readers who are not already familiar with it may have ample material to construct such a curve for themselves. Simple as this is, the amount of information conveyed to a student by actually constructing such a curve is invaluable, and no one who has not constructed one can afford to neglect this exercise.

The curve we get shows position and time; what we want, however, is the speed at successive instants. The speed of motion is seen by the slope, the steepness, of the curve, and we can apply this test to the two crests, one above and one below the horizontal line; here, of course, the curve has no steepness at all, it being absolutely horizontal *just at those two points.* Elsewhere we see, starting, say, from the top crest, that the slope of the curve gets steeper and steeper till it crosses the middle line, that is, the piston moves faster and faster; having passed the middle line the speed gets less and less until the piston comes to rest at the point of reversal. The curve reveals the fact that the motion of the piston is never the same for two successive instants, unless, indeed, one imagines two instants of time inconceivably near to one another at the middle of a stroke. It is obvious that, at the end of a stroke, the piston must come to a standstill in order to reverse, and here, therefore, the motion is nothing, while the *change* of motion is most rapid. At the middle of the stroke the curve is uniformly steep for a very short time, and hence the speed is constant just there, so that its change is zero while its value is at a maximum; except at such points, at the middle of each stroke, the motion is always changing.

Now let us consider the bearing of all this upon the alternating current circuit. The curve is, of course, a curve of sines, and it is usual in dealing with alternating current problems to assume that the E.M.F. of the commercial alternating current generator follows the law of sines; that is, that the curve we have drawn would represent the connection between E.M.F. and time, just as well as it represents the connection between piston position and time. The reason for this assumption is that it is extremely difficult to deal with many problems on the assumption of any more complex law, and it is found in practice that the E.M.F. curve of commercial machines does not depart very widely from this particular shape.

In considering alternating *currents*, we shall consider sinusoidal waves of electricity, and our curve may be used to represent *current strength* plotted vertically against time plotted horizontally. In point of fact, the *electricity* oscillates to and fro in the circuit just as did the water in the pipe of Fig. 309; but we will defer the consideration of the precise way in which the behaviour of the water is analogous to the alternating current until we come to investigate the effect of a capacity. For the present it will suffice to follow the assumption that the *current* curve is a sine curve. It next follows, therefore, that it has the characteristics already pointed out, and the current is thus *always* changing, except for two instants of time (the upper and lower crests) in each period. It further follows from this that the effect of self-induction is always at work except at these two instants of time. Now, although the current is always changing, like the speed of the piston, we have not yet seen how it changes. Mathematically it is easily expressed now that we have assumed it to follow a sine law. If C_t means the current at any instant, and f the frequency, that is the number of complete periods per second, $C_{\text{max.}}$ being the value at the crest, then

$$C_t = C_{\text{max.}} \sin. 2 \pi f t$$

and $$\frac{dC}{dt} = 2 \pi f C_{\text{max.}} \cos. 2 \pi f t$$

the value of $\frac{dC}{dt}$ being the rate of change at the instant t. For those readers, however, to whom this mode of expressing matters is not clear, we may argue as follows: In our curve, Fig. 310, time is plotted horizontally and current strength vertically; hence, if the current makes a big change in a short time, the slope of the curve during that period will be steep. On the other hand, if the current makes but little change in a lengthy time, the slope will be barely perceptible; thus the slope of the current curve is an indication of its rate of change. If, however, we look at the current curve we find that, so far as slope is concerned, it may have one of three characters. The slope may be like the slope of handwriting, when, as time passes, the current is getting greater. Such a slope is called a positive slope, since with an increase of time we have an increase of the quantity. So to the crest of the curve. Just before reaching the crest, the slope, of course, gets continually less, until at the very top of the curve there is the absolutely horizontal portion. It is of no matter how small the horizontal portion is, it is obvious there must be a portion that is horizontal, since the curve bends over. This is the second character the slope possesses, and here it is clearly nothing, it is horizontal. Passing on, the curve again acquires a slope, but of the opposite kind to the one with which it started, and if the former was regarded as positive this must be regarded as negative, since an increase in the time elapsed is accompanied by a *decrease* in the current; in fact, as time continues, the current not only decreases, but reverses and becomes increasingly negative, until the lowest point has been reached, when the slope is once more zero. In character, then, the slope may be positive, zero, or negative, and it may have varying degrees positive or negative. A close and careful inspection of the curve will show, however, at once, that the slope is greatest just where the curve cuts the horizontal line, the axis of time, and the reader may easily for himself* by graphical means follow out the changes which the slope undergoes in a whole cycle.

All these results are expressed easily and briefly by the mathematical expression given above—

$$\frac{dC}{dt} = 2 \pi f C_{\text{max.}} \cos. 2 \pi f t,$$

and this, again, has been translated into graphics by the curve marked $\frac{dC}{dt}$ (Fig. 311). In order, now, to find out the magnitude of the back E.M.F. at any instant, we have (page 353) to multiply this quantity, which is the rate of change of the current, by the coefficient of self-induction L. Or, since the maximum value of cosine $2 \pi f t$ is 1, if we are given the frequency we can at once write

---

* *See* Appendix to Section VI.

$$E_{\max.} = 2 \pi f \text{ L } \text{C}_{\max.}$$

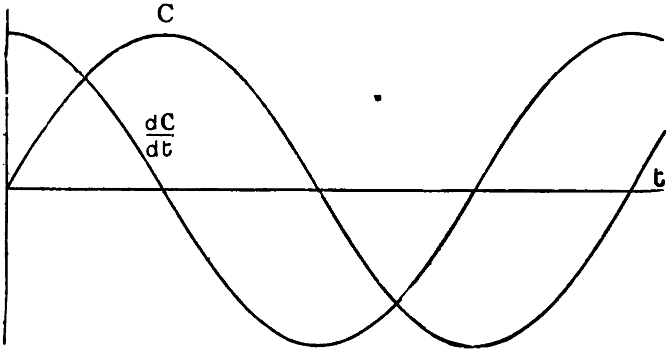


FIG. 311.

If the permeability remain constant, as is the case when the coil has an "air core," the magnetism is at every instant strictly proportional to the current, and we may therefore draw two curves as in Fig. 312, one showing the way in which the current changes as time goes on, and the other how the magnetism changes. The parts of the curve that lie above the horizontal line indicate that the current is flowing in one direction round the coil, which we will call the positive direction (say, clockwise, looked at from the left-hand end), while where the curve lies below the horizontal line it indicates that the current is flowing in the reverse direction, which we will call the negative. The magnetism must, of course, follow, in character, the current curve precisely, being at every instant proportional to the current, and having a sign determined by that of the current. This is consequent upon there being no iron in the core. The presence of iron would not only upset the proportionality, but would, by hysteresis and eddy currents, delay the reversals. In order to fix our ideas we may consider these two curves to relate to a coil of wire having the following dimensions:

Number of turns ...	S =	200 (in two layers)	
Outside diameter...	d_1 =	5·05 cm.	... = 1·99″
Inside „ ...	d_2 =	6·05	... = 2·38″
Mean „ ...	d =	5·55	... = 2·185
Internal area ...	a =	20 sq. cm.	... = 3·1 sq.″
Length	1 =	25·4 cm.	... = 10″
Total flux per ampere allowing for leakage	$N_1 = \frac{4\pi}{10} \frac{S_a}{1} \left(\frac{1-\frac{d}{2}}{1}\right)$ $= 176·5$		

Crank makes one revolution in 180 seconds. Length of crank to represent 10 amperes.

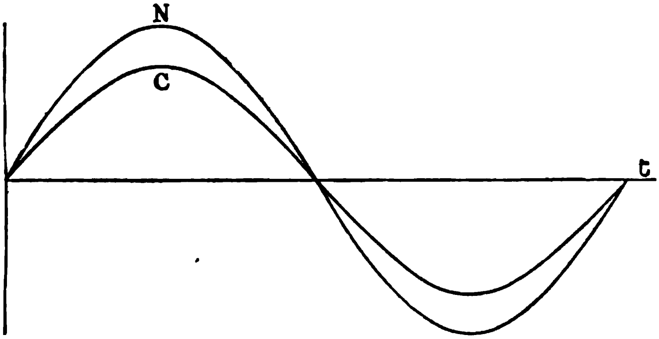


FIG. 312.

Using these figures we obtain for C_t and N_t (the currents and fluxes at the instant t) the values given below. The numbers in the column t give the number of seconds elapsed from the instant at which we start to count time.

t	C_t	N_t	t	C_t	N_t
0	0	0	95	− 1·736	− 306
5	1·736	306	100	− 3·42	− 604
10	3·42	604	105	− 5·00	− 883
15	5·00	883	110	− 6·43	−1135
20	6·43	1135	115	− 7·66	−1351
25	7·66	1351	120	− 8·66	−1531
30	8·66	1531	125	− 9·397	−1660
35	9·397	1660	130	− 9·848	−1738
40	9·848	1738	135	−10·00	−1765
45	10·00	1765	140	− 9·848	−1738
50	9·848	1738	145	− 9·397	−1660
55	9·397	1660	150	− 8·66	−1531
60	8·66	1531	155	− 7·66	−1351
65	7·66	1351	160	− 6·43	−1135
70	6·43	1135	165	− 5·00	− 883
75	5·00	883	170	− 3·42	− 604
80	3·42	604	175	− 1·736	− 306
85	1·736	306	180	0·00	0
90	0·00	0	185	+ 1·736	+ 306

If we wish to show how the E.M.F. of self-induction acts we have but to determine the *rate* of change of the magnetism. This, as we have already pointed out in the case of the current curve, is indicated by the steepness of the curve, the magnetism changing most rapidly where the curve is steepest, and hence we have the two points of greatest rate of change where the curve crosses the horizontal line. Two such successive points are, however, not alike, for one of them is canted to the right, and the other is canted to the left, and the easiest way just now to solve the difficulty thus raised is to have recourse to Lenz's law. The E.M.F. of self-induction always opposes the change of current; indeed, we commonly call it the "back E.M.F." of self-induction, hence at the point 0, when the current is growing and becoming positive, we must expect the E.M.F. of self-induction to be negative opposing this change. As the current rises to its positive maximum its *rate* of rise becomes less, and therefore the back E.M.F. of self-induction becomes less until at the point when the crest is reached, and the rise ceases, the E.M.F. of self-induction is nothing. Now the current begins to decrease, though slowly, and the E.M.F. of self-induction (ever opposing a change) must necessarily be positive, and must be of increasing magnitude as the rate of decrease of the current gets faster. Following out this train we arrive at the curve for E.M.F. of self-induction shown at p L C in Fig. 313. Here p stands for $2\pi f$, and the product p L C gives the height, in volts, of the crest of the curve if C is the height in amperes of the crest of the current curve. Comparing this with the expression just given on page 358, we find that if p L C is the maximum E.M.F. of self-induction, and p C is the maximum rate of change of the current, L must be a multiplier involving both the number of turns of wire and some quantity referring to the flux, since these two must be involved in the cutting which causes the E.M.F. A little reflection will lead to the conclusion that L is the number of hundred million linkages (of lines and turns) *per ampere* in the coil. In a solenoid then, $L = N_1 \times S \times 10^{-8}$, N being the flux per ampere, or due to one ampere. This is clearly the E.M.F. in volts caused by the decay of the flux (and therefore a current of one ampere) in one second. This agrees with the definition on page 353. For the present coil $L = 176{\cdot}5 \times 200 \times 10^{-8}$, or 0·000353 henry.

Mathematically the whole of this reasoning may be given as follows:—

$$N_t = N_{max.} \sin. 2\pi f t = k\, C_{max.} \sin. 2\pi f t.$$

$$\begin{aligned} E_t &= \frac{d\,N_t}{dt} \times S \times 10^{-8} \\ &= -2\pi f N_{max.} \cos. 2\pi f t \times S \times 10^{-8} \\ &= -2\pi f k\, C_{max.} \cos. 2\pi f t \times S \times 10^{-8}. \\ E_{max.} &= -2\pi f\, N_{max.} \times S \times 10^{-8} \\ &= -2\pi f k\, C_{max.} \times S \times 10^{-8}. \end{aligned}$$

This last expression shows that the E.M.F. of self-induction depends on four independent things, viz.: (1) f the frequency, or speed of the crank; (2) k a factor depending on how the coil is made—it is the area of the coil, multiplied by the turns per centimetre, multiplied by 1·26; (3) C, the maximum current; (4) S, the total number of turns. That it depends on the rate of rotation of the crank, those who have no mathematical knowledge can readily see by bearing in mind that the steepness of the curve indicates its rate of change. If the crank revolved at twice the speed, for example, then there would be just twice as many ripples in, say, five seconds, as there are in Fig. 310, but each ripple would be just as big as before, and if the reader draws for himself a second curve having twice as many ripples, he will see that the steepness of the curve is increased, and, indeed, that it is just twice what it was before. Also, it depends on $C_{max.}$, for, if the height were greater in the same period, the like result would follow.

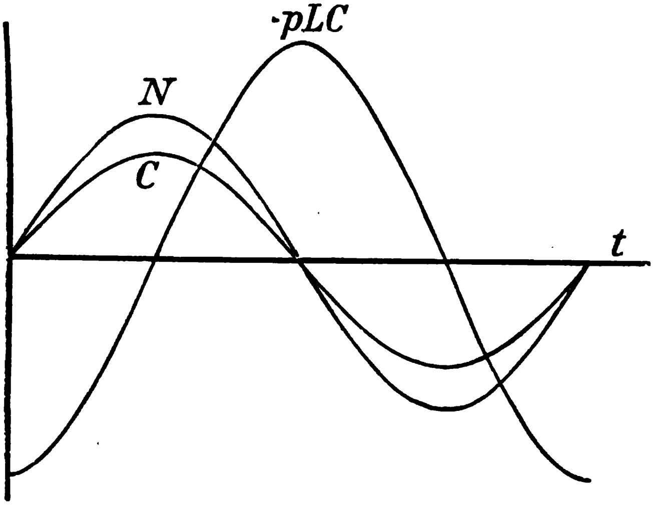


FIG. 313.

POWER IN AN ALTERNATING CIRCUIT.

To a student accustomed only to direct current working it is somewhat startling to be told that if he reads the amperemeter and voltmeter on an alternating current switchboard and multiplies the two readings together, he does not necessarily get by their product the watts being delivered to a circuit. This is, however, the case, the reason being that the power that is actually delivered to the circuit depends upon the phase relationship between the pressure and current. The "phase" of an alternating quantity is its condition. Two currents, one of which is growing to a positive maximum, while the other has passed the maximum and is declining, are said to be "out of phase with one another. To be perfectly "in phase" they must perform their operations of reversing, etc., precisely together; they must be perfectly *in step* with one another. The same remarks apply to a voltage or a current. Of course, the amperemeter and voltmeter say nothing at all about this. Let us consider in the first place how the phase relationship between pressure and current can affect the true power being delivered. Let us suppose first of all that we have the two perfectly in phase, that is to say, that when the pressure is at its positive maximum value the current is also at that value, that the two decrease together, pass through zero at the same instant, reach the negative maximum values together, and so on throughout the whole cycle. The total energy delivered in a whole cycle of operations is, obviously, the sum of all the products of amperes, volts and time taken at every instant throughout the cycle, or expressed mathematically it must be

$$\int_0^{2\pi} V \times C \times dt.$$

Now when the two are perfectly in phase both are positive throughout the same period of time, and then again both are negative throughout an identical period of time; hence the product of amperes and volts is at all times positive, and if we know all the products of amperes, volts and time throughout the first half of a period, we may double it and obtain an accurate result for the product over the whole period. This is shown in Fig. 314, which refers to a current of 20 amperes maximum, exactly in phase with an E.M.F. of 100 volts maximum. The curve marked W gives the watts at every instant to the scale of kilowatts, and the energy delivered in one period is the height of the watt curve multiplied everywhere by time: this is given by the *area* included between the W curve and the axis of time. This area lies wholly above, *i.e.* on the positive side of the axis of time. Next, let us consider the case in which the current has become displaced in the circuit with reference to the E.M.F. by a quarter-period, the maximum displacement that is ever attainable, and only so, strictly speaking, in theory. During the first quarter-period, as is at once seen by reference to Fig. 315, the E.M.F. is positive while the current is negative, and hence the products throughout this period of time will all be negative. During the ensuing quarter-period the E.M.F. will remain positive, and the current has changed to positive also, hence their products will also be positive. In the next quarter-period the current is positive and the E.M.F. negative, hence the products are negative; while in the final quarter-period of our cycle the current is again negative, while the E.M.F. also remains negative, giving for this portion of the cycle positive products. These results are embodied in the diagram Fig. 315, from which we see that if a whole period or cycle be considered, it may be regarded as consisting of four portions, two of which give positive values for the power and two give negative. Moreover, it is at once obvious from the symmetry of the diagrams that the sums of the products in all four quarter-periods are identical, and when multiplied by time give four equal areas. Two of these are positive and two negative, hence, if we add them all up, their total area will be zero, which leads us to the, at first sight, surprising result that we may have an alternating current in a circuit, and, of course, an alternating E.M.F. producing it, and yet no power whatever being delivered to the circuit. As, however, we have stated above, this condition is only attainable theoretically; in practice it never can be perfectly attained. The obstacle to its attainment in practice is, of course, the possession of resistance by all the conduc-

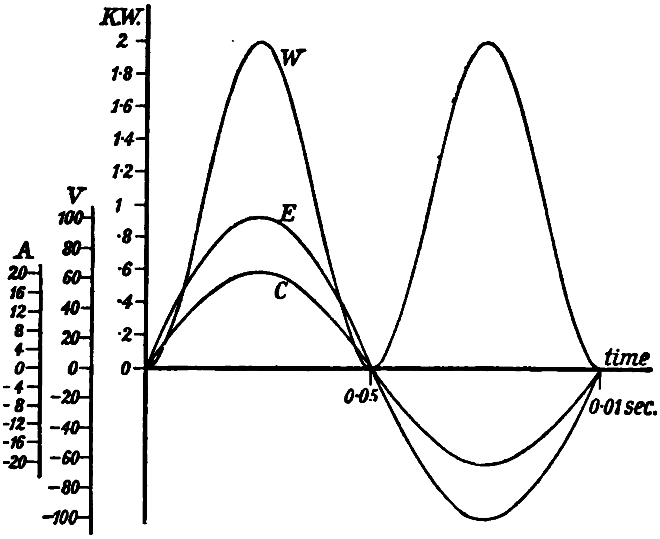
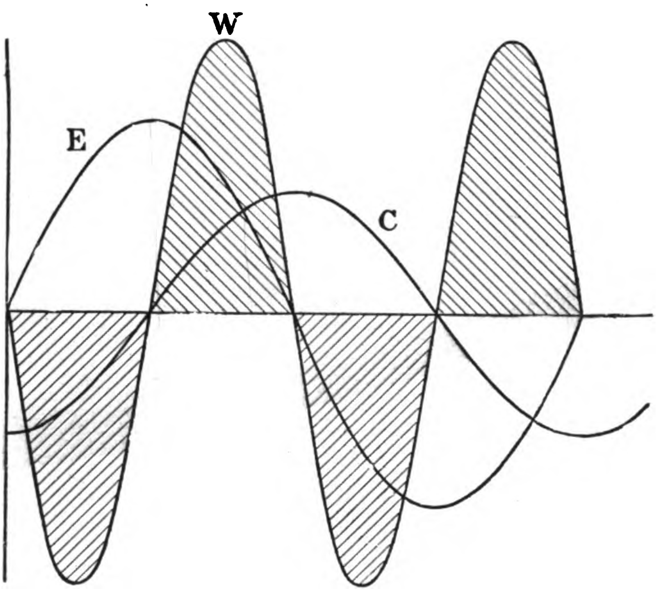


FIG. 314.

tors in the circuit; but even when we take duly into account the resistance of the conductors we may still have such a case as 50 amperes flowing at 100 volts supplying possibly only two or three watts instead of the 5,000 watts, which would inevitably be supplied in a direct current circuit with that current and pressure.



▧ = Positive work: i.e. work done by, given out from the circuit.

▨ = Negative work: i.e. work put back into the circuit.

FIG. 315.

Now, while it is unusual to find current lag by so much as a quarter period, it is quite common, and, in fact, almost inevitable, to have an alternating current lag by some less amount. When this is the case we can best arrive at what is actually going on in the circuit by reference to the diagram in Fig. 316. Instead here of assuming that we have an E.M.F. at work and endeavouring from that to arrive at the current and its phase displacement, we will assume that there is a current, and from that make calculations to find what the E.M.F. must be to drive it, and how it must be related in phase to the current. The curve marked C represents, then, an alternating current which we suppose to be flowing in a circuit that is possessed both of inductive properties and resistance. If the circuit possesses inductance, the power, that is, of producing magnetic lines, it will have the property of self-induction (*see* page 348), and if we know the details of the circuit we can calculate the coefficient of self-induction and hence the magnitude of the self-induced E.M.F., when we are given the frequency and the magnitude of the current. The magnitude, however, of the self-induced E.M.F. is not the only thing we need to know concerning it; we must take account of its phase relation with the current. This induced E.M.F., as was pointed out on page 348, is always in opposition to the current, so that with reference to the flow of current in the circuit it is negative in its effect, and we must draw our curve accordingly as shown at *p* L C in Fig. 316. The induced E.M.F. in the circuit is a new factor of which Ohm's law took no account, and if we wish to restore the conditions to which Ohm's law applies we must introduce an E.M.F. which at every instant will effectually nullify that one which is the effect of self-induction. In other words, if we introduce an E.M.F. which at every instant is equal and opposite to the E.M.F. of self-induction, these two will cancel one another, and we may then consider the circuit as being free for the operation of Ohm's law as ordinarily written. Let us then introduce into the circuit such an E.M.F., regarding it as being a part of the requisite E.M.F. to be supplied to drive the current through the circuit. It is shown by the dotted curve at $-p$ L C in the diagram. Now, then, we can apply Ohm's law. The resistance being known to be R ohms, we need at every instant (by the law) an E.M.F. equal to C R, in order to get the current through the resistance. But the current is continually changing; so, too, must this E.M.F. change. We can easily draw the curve to represent the E.M.F. required at every instant to overcome the resistance, by multiplying the current in amperes at every instant by the resistance in ohms, and plotting the product so obtained to the scale which we have adopted for E.M.F.'s. At this point, then, we have four distinct quantities to consider in the circuit: the current first; then the E.M.F. of self-induction; thirdly, the E.M.F. we have introduced to nullify this; and, finally, the E.M.F. which we conclude is necessary to overcome resistance. These four are lettered (1) C, (2) p L C, (3) $-p$ L C, (4) C R. Nos. (3) and 4 have to be supplied, and if we wish to know what is wanted at every instant we must add Nos. 3 and 4 together. If we do this on the diagram by adding the ordinates of 3 and 4 at several points we shall get a fifth curve, as is shown in the diagram at E.

A slow and careful consideration of these curves, and the simple reasoning by which they have been arrived at, is of very great value to a student when first entering upon the study of alternating currents. For further graphical work, however, the curves are too cumbersome. They are almost indispensable in approaching the subject owing to the exceedingly clear picture they give of the sequence of the several quantities involved, but they become unwieldy directly the circuit becomes complicated and directly rapid calculations are required. Of course, they may always be dispensed with by the aid of a little elementary mathematics, if such mathematics include the easy portions of the differential calculus. Indeed, a knowledge of the elements of the differential calculus is of enormous service to an electrical engineer, and will carry him a very great distance, while on the other hand the acquirement of such knowledge is exceedingly easy.

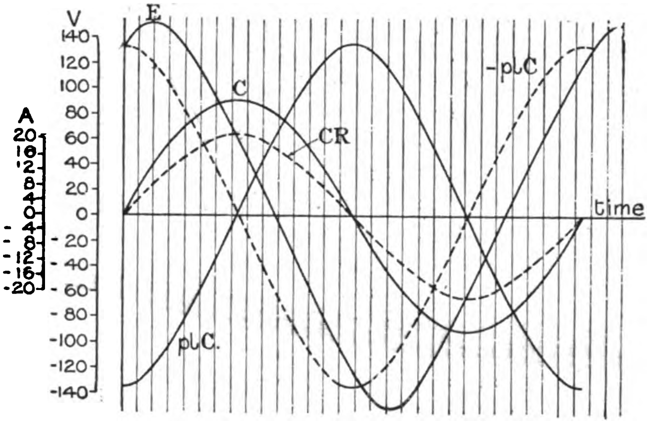


FIG. 316.

An inspection of the diagram in Fig. 316 reveals the following interesting facts. The diagram differs from those shown in Figs. 314 and 315 essentially by the introduction of the portion marked C R. In the latter the circuit was supposed to possess a negligible amount of resistance, and hence the C R curve was properly omitted, and the current was lagging by a quarter-period. In the present case the current lags by an amount less than a quarter-period. This lag, whatever its amount, is clearly due to the necessity of giving the E curve a factor which nullifies *p* L C, and hence the lag is due to self-induction in the circuit. Further, this factor (−*p* L C) increases the total E above what it would be if C R only had to be supplied. It follows, then, that for a given C, E has to be greater than it would have to be if self-induction were absent; conversely, therefore, the presence of self-induction diminishes the current. If it were absent the current would clearly be perfectly in phase with the E.M.F. Hence, self-induction introduced into a circuit supplied at a given E reduces the amplitude of the current and causes it to lag.

By reference to the following diagrams, Fig. 317, we next see that, without altering the magnitude of the curve *p* L C, we can alter the position of the resultant curve E by altering the amplitude of the curve C R. If we increase the C R curve in magnitude we bring the resultant curve E more nearly into phase with the current C, whereas the smaller the C R curve the more nearly does the amount of lag approach to a quarter period. If, however, we had kept the C R curve constant and varied the magnitude of the *p* L C curve we should have found that the greater the *p* L C curve the more the lag, and *vice versa.* These operations alter the magnitude, of course, of the E curve as well as its position. If we vary both simultaneously, we again alter the total magnitude of the E curve as well as its phase position; but it would appear that if we alter the C R and the *p* L C curves simultaneously so as to get the same resultant magnitude of the E curve, in every case the phase of the E curve with regard to that of the C curve would be determined by the *ratio* of the C R to the *p* L C curve. This is easily shown to be the case when we abandon curves for the graphical method known as clock diagrams. Clearly each of the curves shown in the preceding diagrams can be just as well represented by a crank from which the curve may be developed as was done in Fig. 310. The cranks are supposed to rotate clockwise, hence the name "clock diagrams." Before, however, we pass to this method of treating the subject we must complete the application of the curves to

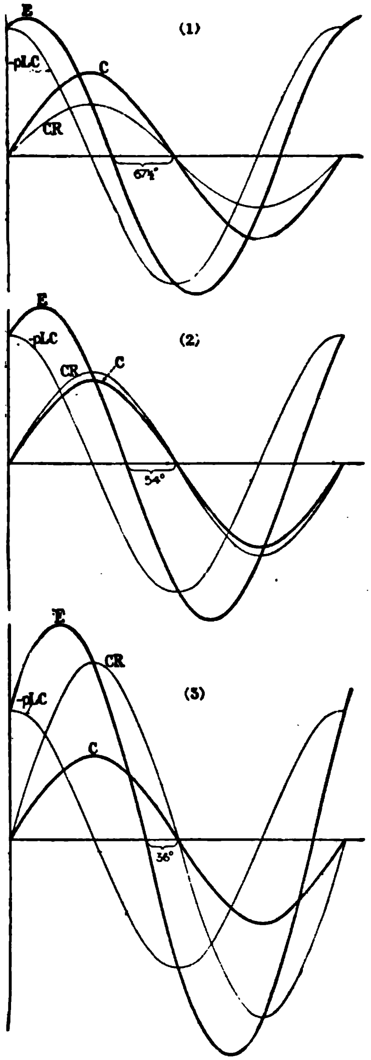


FIG. 317.

elucidate the amount of power in the circuit when the current lags by less than 90 degrees. In Fig. 318 the curves represent respectively the same quantities as were plotted in Figs. 315 and 316, only the lag here, instead of being 90 degrees, is about 30 degrees. This diagram shows that in one complete period there are, as before, four distinct periods, two of positive power and two of negative, but that in the present case the periods of negative power are less in duration and have a less total height than those of positive power. The area, therefore, under positive power, representing the total work done, is, on the whole, greater than the area under negative power, and the net result is a positive area representing the total work done in one period. An area here represents work, of course, since it is the product of height and length, height being power and length being time (see page 8, Section I.). The total area when the lag is ϕ is the apparent area multiplied by cosine ϕ, by the following reasoning

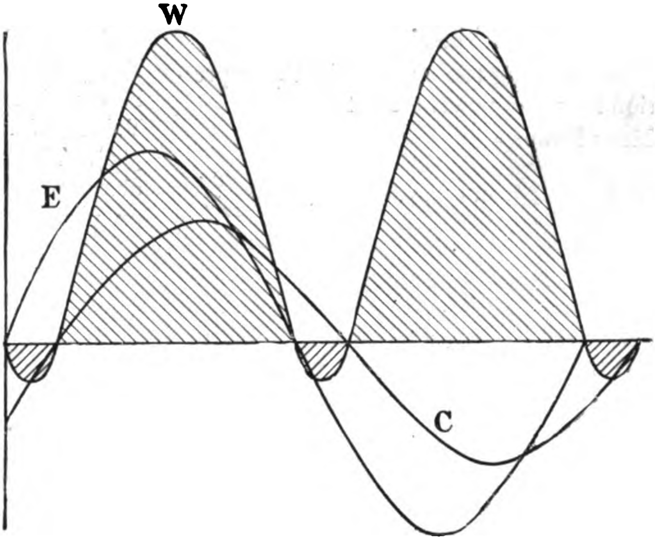


FIG. 318.

Since the curves are symmetrical we need only consider what goes on in half a period. To get the mean power in this time we must find the total work done and divide by the time; this will give us the mean rate of working, or power.

The total work done is the sum of the instantaneous values of the watts, multiplied by the time or

$$\int V \times C \times dt.$$

The work done in half a period if τ is the number of seconds for a complete period is

$$\int_0^{\frac{\tau}{2}} V\, C\, dt.$$

We assume $V = E_{max.} \sin. \theta$, and since the current lags by ϕ, $C = C_{max.} \sin. (\theta - \phi)$. Substituting these values and dividing by $\frac{\tau}{2}$ to get the mean rate of working we have mean power =

$$\frac{2}{\tau}\int_0^{\frac{\tau}{2}} E_{max.} \sin. \theta \times C_{max.} \sin. (\theta - \phi)\, dt.$$

Now, putting angular limits for time limits, always remembering that for mathematical work angles are measured in radians, and, further, that one period is equivalent to one revolution, that is, to 2π radians, we have,

$$\text{Time of 1 period} = \tau \approx \frac{1}{f} \approx 2\,\pi.^{*}$$

The angle $2\pi f$ is swept out by the crank in one second, therefore the angle π (half a period) is swept out in $\frac{1}{2f}$ second.

---

* $\approx$ Stands for "is equivalent to."

Also t secs.: 1 sec. :: θ radians: $2\pi f$ radians.

$$\therefore \quad t = \frac{\theta}{2\pi f}.$$

$$\therefore dt = \frac{d\theta}{2\pi f}.$$

Substituting these values in the expression for mean power we get

Mean Power =

$$2f\int_0^\pi \text{E}_{\text{max.}} \sin.\,\theta \times \text{C}_{\text{max.}} \sin.\,(\theta - \phi)\frac{d\theta}{2\pi f}$$

$$= \frac{\text{E}_{\text{max.}}\,\text{C}_{\text{max.}}}{\pi}\int_0^\pi \sin.\,\theta\,\sin.\,(\theta - \phi)\,d\theta,$$

$$= \frac{\text{E}_{\text{max.}}\,\text{C}_{\text{max.}}}{\pi} \times \frac{\pi}{2}\cos.\,\phi,$$

$$= \frac{\text{E}_{\text{max.}}\,\text{C}_{\text{max.}}}{2}\cos.\,\phi.$$

Cos. ϕ is given the name "Power Factor." The presence of 2 in the denominator will be explained under the heading "Virtual Values of Alternating Quantities" (page 386). Those readers who do not follow the above reasoning will find the explanation on page 369 very much simpler.

CHAPTER II.—ALTERNATING CURRENT CIRCUITS.

CLOCK OR VECTOR DIAGRAMS — IMPEDANCE — CAPACITY — PERMITTANCE — REACTANCE — INDUCTANCE AND PERMITTANCE IN SERIES — IN PARALLEL — PRACTICAL APPLICATION — RESONANCE.

We have already made use of a rotating crank to exemplify the sequence of phenomena in an alternating current circuit, and we shall now proceed to carry the thought further. Diagrams based on this have been in use some fifteen years, having been elaborated about 1885 by Mr. Blakesley, who gave them the name of clock diagrams. It may be well to remark here, that in mathematical treatises cranks are usually taken to revolve counter clockwise, since that is the direction which is considered positive in works on trigonometry, and in the vector and rotor calculus. In purely technical works, however, it is the almost invariable custom to give the cranks a clockwise direction of rotation and we shall, of course, adhere to this practice.

The great value of the clock diagrams lies in the fact that we can indicate any one of the various quantities which are changing by a line rotating about one end, and supposed to represent a crank. If we give these lines their proper position in relation to one another, we can get from the diagram at once all the information which we want, and it is by no means difficult to give the cranks their proper relative positions.

Directly we convert the curve diagrams which we have just been considering into vector diagrams, the actual angle of lag, by which the current is behind the E.M.F. stands out much more clearly before us. In order to ascertain the angle of lag in the curve diagrams it was necessary to have reference to the axis of time in the first place, and then to remember that one complete period was equivalent to 360 degrees. The clock diagram, Fig. 319, is arrived at by precisely the same reasoning as the curve diagram, but the alternating quantities have their maximum values represented by the lengths of cranks, all the cranks revolving about a common

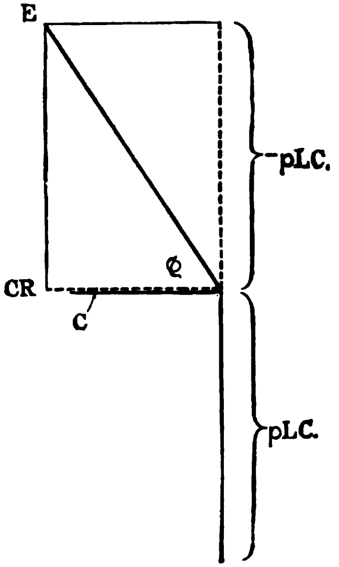


FIG. 319.

centre where they meet, at a uniform velocity, and making as many revolutions per second as there are periods per second. We will now build up a vector diagram to display the same facts as the curve diagram, Fig. 316. We will begin with the current, which is represented by the crank C. We can choose, of course, any scale whatever for the measurement of current, for example, $\frac{1}{8}$ inch to the ampere, or any other convenient scale that may occur to us. The cranks all revolve clockwise, or right-handedly, and since the back E.M.F. of self-induction follows, as we have already seen (page 363), a quarter of a period behind the current, we must represent it by a crank 90 degrees behind the current crank. It is shown in the diagram by the crank p L C. The E.M.F. necessary to drive the current through the resistance of a circuit is given by a crank which is in step with the current and whose length must be equal on the volt scale to C R. The generator now therefore must supply, firstly an E.M.F. to neutralise p L C, and secondly it must supply C R. Obviously the voltage necessary to neutralise p L C will be represented by a crank of equal length and 180 degrees ahead of it. This is shown by the dotted line $-p$ L C. We thus have the two components, $-p$ L C and C R, which give us all the information we want to enable us to say what precisely is the E.M.F. required. The cranks represent two forces, and we may compound them like any other forces by making a parallelogram and finding the diagonal. The diagonal is shown at E, and represents the E.M.F. that must be supplied to the circuit to get that current C through the resistance and self-induction. The length of the crank E denotes the magnitude, and its position in relation to the crank C denotes the phase of the E.M.F. The student must clearly understand that these cranks are all supposed to be revolving continuously, and in making our diagram we have assumed that it is in our power suddenly to arrest matters at some desired instant while we proceed to portray by the above reasoning the various relationships in question. It is, of course, quite immaterial at what particular instant we arrest the revolving cranks; we should always get precisely the same numerical result; the only difference that would arise from making our investigation at different instants would be in the actual position of the cranks in space — their relative positions would remain unaltered so long as current, resistance and self-induction are the same. A very good mental picture of what is going on in the circuit may be obtained by imagining what would happen with the following arrangement. Let a number of glass tubes filled with different coloured liquids be mounted on a very slowly revolving axle, in such a way as to represent the various cranks shown in the diagram, and let the coloured shadows of these tubes be thrown by a strong light on to a screen placed parallel to the axis about which the tubes rotate. Now if the axle be very slowly rotated the shadows of these coloured tubes on the screen will rise and fall in regular succession above and below a horizontal line given by the shadow of the axle, the heights of the shadows above the axle representing positive quantities, and their lengths below the axle negative quantities. Thus we might have a tube filled with red liquid for the current crank, one with blue liquid at 90 degrees behind it for the self-induction E.M.F., a pale blue one to represent the E.M.F. opposing it, a black one for the C R crank, and a white one to represent the total E.M.F. to supply the circuit.

We have seen already (page 361) that when a current lags 90 degrees behind an E.M.F., the power transmitted in a complete cycle is 0, and that, whatever the angle of lag, the power transmitted is given by the product of current and E.M.F. multiplied by the cosine of the angle of lag.

In this diagram, Fig. 319, we see that the angle ϕ between the C crank and the E crank is determined by the relation between the two components C R and and $-p$ L C. The need of $-p$ L C throws the E crank in advance of the C R, and hence also of the C crank. We usually say it makes the current lag behind the E.M.F.

Now, if we consider the two components of E, we see one ($-p$ L C) has a 90 degrees phase displacement in advance of C, and hence only represents a condition of surging energy, that is of work alternately expended in building a magnetic field by the circuit and returned to the circuit as the field dies. This goes on with no balance in favour of or against the circuit. The component C R is, on the other hand, right in phase with C, and these two represent power to the full. The magnitude of C R is clearly E cos. ϕ, and hence $C \times (E \cos. \phi.) = C^2 R$, or the power delivered by the current in heat. If in addition to C R there were in circuit an E.M.F. exactly in step with the current, but exactly opposite to it, we should have to supply an equal and opposite E.M.F. to nullify it, and this would be in phase with the current. It would, therefore, in conjunction with the current, also represent power without any deduction.

In the light of clock diagrams, therefore, cos. ϕ appears as the factor by which we must multiply the total E to find the component in phase with the current, and combining with it to deliver power.

If the angle be less than 90 degrees the power transmitted has a finite value, although exceedingly small if the angle approaches anywhere near 90 degrees. In practice we find a load which does very nearly fulfil this condition when a central station is supplying a network of conductors to which the primary circuits of a number of unloaded transformers are connected. There will be then a fairly large current at a high voltage delivered from the station, but the angle of lag will be so great that the power transmitted is very nearly nothing, so small, indeed, as to be nearly negligible. It is most unfortunate that when this first came to be recognised the current so flowing from the station, and associated with little or no power, came to be called a "Wattless Current." There is no more reason, in point of fact, for saying that the current is wattless than there is for saying that the E.M.F. *driving it* is wattless. Since the E.M.F. of supply is kept constant, there is a subtle temptation to the beginner to regard the power delivered as the property of the current only, whereas watts are the product of E.M.F. and current, and it is absurd to suppose that they are due to one more than to the other. Moreover, the term "wattless current," has introduced a great deal of difficulty to students in approaching this matter. In the first place, it is quite impossible to have a truly wattless current flowing in *any* circuit, or, to express it more precisely, it is impossible to have a current flowing in a circuit without the expenditure of some power. This was duly recognised, and in order to get over the difficulty it was said that the current might be regarded as being made up of two components at right angles to one another, one of which—a small one—was in step with the E.M.F. and the other 90 degrees behind it. Of these two components the small one was the "power current," and the one which lagged by 90 degrees was called a "wattless" current. The explanation is all very well as a piece of fine imagination or as a mathematical device, but is utterly misleading as regards physical facts. As a result of the phraseology, language was commonly used which appeared to convey the idea that there were two currents in the circuit, the power current and the idle current, and, of course, the bare idea of two different currents at one time in the same circuit is altogether contrary to working theory, particularly as they are simultaneously flowing in opposite directions half the time; hence the term wattless current has been the source of much difficulty and obscurity to students. A far preferable way of treating the circuit, in the writer's opinion at least, is to adhere to the theoretically correct assumption of only one current in the circuit, and to split up the E.M.F., rather than the current, into two components at right angles to one another. The presence of two, or even of many E.M.F.'s simultaneously at work in the same circuit is neither theoretically incorrect nor foreign to experience, and is, on these grounds alone, superior to the old method. We can then speak of the applied E.M.F. leading ahead of the current, and of its being resolved into one component, in step with the current, associated with work given out, and another component exactly 90 degrees ahead of the current and associated with surging energy and no total work or power. It is quite possible physically for an E.M.F. to exist by itself apart from any current, while it is impossible for a current to exist apart from an E.M.F. driving it. The only change in our phraseology needed then is "wattless E.M.F." This wattless E.M.F. very accurately and truly represents the physical facts, it merely stands for the E.M.F. in the circuit which is entirely occupied in coping with the self-induced E.M.F. This latter, as we have already seen, is associated with a magnetic field, which field, on the whole costs nothing in power, but acts precisely as a spring taking in and storing work when it is compressed, and giving out that same work as it expands, a wattless operation when carried through any complete cycle. So the field, apart from any iron which conducts it, takes in work in its formation, but restores it perfectly when it dies away; the alternations of field causing a surging of energy out of and back into the electric circuit; a wattless operation when carried through a complete cycle. (*See* Fig. 315, page 362). The writer has always found that students readily accept and grasp this mode of presenting the subject, while the mere mention of a wattless current invariably throws their minds into confusion in view of the fact, well known to them, that no conductor is devoid of resistance; from which fact they at once, and correctly, argue, that heat must be produced by *every* current, and that there can be, therefore, no such thing as a wattless current.

IMPEDANCE.

So long as we dealt with continuous currents we needed only to consider one property of the circuit, namely its resistance, so that if this were known and the E.M.F. were known we had merely to divide the latter by the former and to find the value of the current. We have just seen, however, in the preceding pages, that the alternating E.M.F. applied to the terminals of a circuit may have to contend with more than simply a resistance; part of it may, in fact, be absorbed in dealing with the opposing effect of self-induction. The magnitude of this amount is given by the expression $2 \pi f L C$, while the amount that is necessary to overcome resistance is, of course, $C R$, and, two E.M.F.'s of these magnitudes respectively must be at work at right angles to one another. Both magnitudes are proportional to the current, and hence we shall not disturb their relation in any way by cancelling the letter C from both terms; this shows that we have apparently to deal with a circuit (apart from any current in it) possessed of two distinct properties, that just represented by R, which we call resistance, and that property which is represented by $2 \pi f L$. The letter L we know, it has already been described as representing the coefficient of self-induction. The other quantities are mere numbers, f being the frequency, that is, the number of complete cycles per second of the circuit in question. To the term $2\,\pi f L$ the name "inductance" has been given.

Let us for a moment stop to consider what it is that we mean by the resistance of a circuit, or rather let us consider what the resistance may be taken to mean. The resistance of a circuit is that property of the circuit which expresses numerically the magnitude of the E.M.F. in volts required to send one ampere through it (assuming that it possesses no other property such as inductance or reactance), and we may thus regard the term resistance as almost synonymous with an E.M.F. Again, the property which we call the inductance of the circuit gives us the magnitude of the E.M.F. required to drive one ampere through the circuit, taking into account its self-inductive action *only* and neglecting for the moment any resistance or other property. We may thus say that the resistance of a circuit gives us the voltage necessary to get one ampere through it taking resistance only into account, and the inductance of a circuit gives us the voltage necessary to get one ampere through it taking inductance only into account, but that the volts necessary to get an ampere through a circuit possessing resistance and inductance is given by the diagonal of a parallelogram, one side of which represents resistance and the other inductance. The magnitude of this diagonal will clearly be

$$\sqrt{R^2+4\,\pi^2\,f^2\,L^2},$$

and since it represents numerically the voltage required to drive one ampere through the circuit taking both properties into account, it should be given a name ending in "ance," to make it correspond with resistance and inductance. The name given to it is "impedance." In the diagrams and explanations that we have hitherto been considering we have attacked the circuit from the point of view of current, that is to say, we have assumed a current to be flowing, and have then estimated what E.M.F. was needed. We now, then, have a weapon which enables us to reverse the mode of attack, and to say that if we are given the E.M.F. at work we can calculate the current. We can do it because we know that the impedance represents the voltage wanted to get one ampere through the circuit, and if there are C amperes we shall want C times as many volts, and we may hence use impedance for alternating current just as we used resistance for direct currents, and may write the equation

$$C = \frac{E}{\sqrt{R^2 + p^2\,L^2}}$$

where $p = 2\,\pi f$ as before

By so doing we have arrived at the relations shown in the upper diagram of Fig. 320, where E is the total E.M.F. required to drive C through R and p L. Clearly the other diagonal, marked C I, is equal *in length* to E, and may be used instead, so far as magnitude alone is concerned. The triangle, C R, C I, $-p$ L C, has its three sides all proportional to C, and we shall not therefore alter it in any way except in the scale to which we draw it if we make the sides *equal* to R, I, and p L; which is equivalent to taking the current to be one ampere. This gives us the lower triangle of Fig. 320, known as Fleming's triangle, the hypothenuse I giving the magnitude of the E.M.F. to send *one ampere* through the circuit. Now, although the side I is not in the proper phase relation to the other two, when considered in this light, it gives us what we want. If we have a rectangular parallelogram it is clearly immaterial which of the two diagonals we take; they will both be equal in length, and if direction is of no importance either will serve. In constructing vector diagrams direction was of importance, because we wished to represent the angle of lag accurately, and we consequently took the diagonal which divided the angle between resistance and inductance.

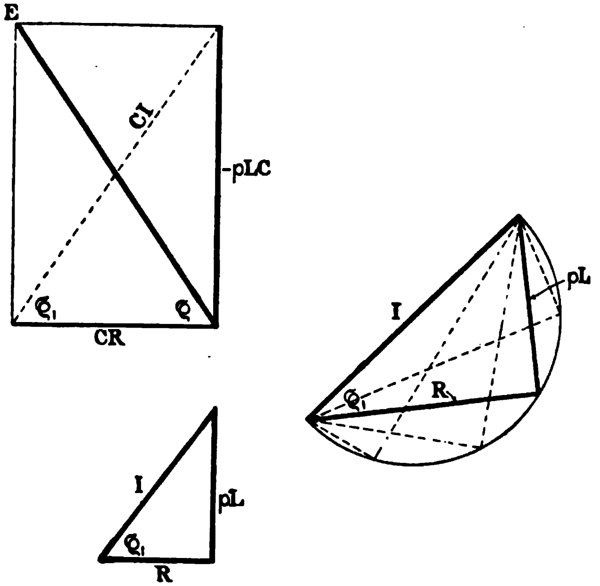


FIG. 320.

Fleming's triangle is composed of resistance and inductance and the other diagonal of the parallelogram, which, in magnitude, of course, represents impedance (*see* Fig. 320). Moreover, since the parallelogram is a rectangular one, the angle ϕ_1 also gives the magnitude of the angle of lag; hence Fleming's triangle at once enables us to calculate graphically the magnitude of the impedance and the amount of the angle of lag without actually completing the parallelogram. This part of our subject must, however, not be left without reference to a further use of this most valuable construction. When we wish to adjust the proportions of inductance and resistance without altering the impedance, all we have to do is to draw a semicircle on a line whose length represents, to scale, the impedance we want. The semicircle is the locus of the right angle of all possible right-angled triangles having the diameter for hypothenuse. These triangles are, of course, right-angled always, and if a chord is laid in the semicircle, of a length to equal p L (to the same scale as that for impedance), the chord to the same point from the other end of the diameter gives the value of R. We see at once how to adjust matters to get the desired current at any given ϕ.

CAPACITY.

Another property of the electrical circuit which, in addition to self-induction, only comes into play when the current is changing, is the property known as the *capacity* of the circuit. Some reference was made to this property in Section I. when dealing with the electrical circuit, and we now have to consider it rather more in detail, particularly as it affects an alternating current circuit. Precisely the same analogue as that adopted in Section I. will suffice if, instead of the rotary pump there indicated, we substitute a reciprocating pump, as has been done in Fig. 321. The consideration of this figure shows two things, namely, that as the piston in the pump oscillates to and fro, the rush of water in and out of it at any particular instant will depend upon the *speed* of the piston and its speed again on its *position* at that instant, hence the rush of water into or out of the condenser will also be dependent upon the position of the piston. Now the connection between position, speed, and rate of change of speed is fortunately simple. Each is the rate of change of the last-named, and if position follows a sine law, speed is a sine curve displaced backwards[*] by a quarter-period, and acceleration another sine curve again displaced backwards by 90 degrees. The rate of change of any sine curve can always be obtained by drawing another leading by 90 degrees.

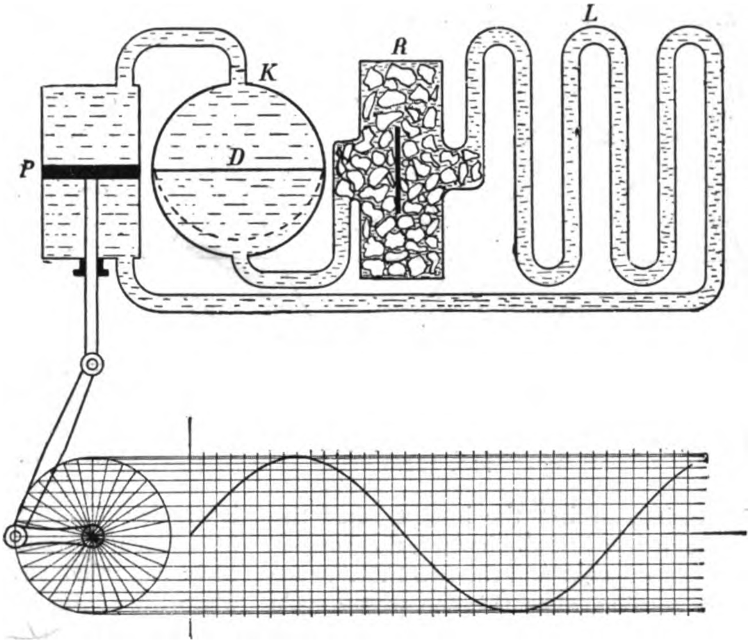


FIG. 321.

To a deplorably large number of students there is little or, at most, a hazy difference between *quantity* and current; we must next, therefore, emphasise our definition of an electric current, or more properly speaking, our definition of what has to be considered the measure of magnitude of an electric current. What we measure when we measure a current is *the rate of flow of electricity*, and by carefully keeping this definition in view any difficulty in considering the effect of capacity in an alternating current circuit should be materially lessened. So far as the analogy goes, the water is *electricity*, its rate of flow is *current*, its volume is *quantity*, and its pressure is *potential.* The piston moves at its greatest speed just when it is in the middle of its stroke, and it will, therefore, be at this instant that the rate of flow into the condenser on the one side and out of it on the other will be greatest. In other words, we shall have at that instant the greatest current. At that instant also the diaphragm of the condenser will not be distended in any way. Expressing all these facts in electrical language, we can say that the current into a condenser supplied by an alternating E.M.F. is greatest at the commencement of the charge, and that at that same instant the back E.M.F. of the condenser is zero (since the diaphragm is unstretched). Since the diaphragm is unstretched no pressure is necessary on the part of the piston to drive the water in, if we neglect any friction in the pipes, but then, as the water enters and the diaphragm stretches, greater pressure is necessary on the part of the piston; also, as the piston advances towards the end of its stroke, producing distension of the diaphragm, its own speed and hence also the rush of water are diminishing, as we see from the curve. We may express these facts electrically by saying that when the current is greatest the E.M.F. driving it is nothing,[*] and that as the back E.M.F. of the condenser rises, so the E.M.F. to drive the current rises, and at the same time the magnitude of the current falls off. Continuing our reasoning in this way, we see that (corresponding to the end of the piston stroke) we reach a point where the two E.M.F.s, namely, the forward and the back, are at their greatest, and the current is at its least, namely, nothing, and that matters then begin to reverse, the forward and the back E.M.F.s diminishing and the current increasing, until at the instant when the condenser is just discharged, the current is at its greatest and the two E.M.F.s are both nothing, after this the whole cycle of operations reverses and then repeats. These facts have been represented by the curves in Fig. 322, and the curves will need no further remark to make them clear, beyond the statement that, since the forward driving E.M.F. of the circuit and the back E.M.F. of the condenser are opposed to one another, it is, of course, necessary to represent the one as positive while the other is negative, and that when the current is flowing with the driving E.M.F. of the circuit it must be considered positive, and negative when against. The reader cannot be urged too strongly to reason out for himself very carefully the connection between the three quantities, forward E.M.F., back E.M.F., and current at every stage of the operations described. It will be quite insufficient for a proper grasp of the matter for him merely to acquiesce in the diagram as shown. It is essential that he should carefully check it for himself at every point, and in particular that he should satisfy himself that no error has been made in the diagram as regards the signs of the quantities at each instant. If the reader does this for himself conscientiously, he may well be surprised at first at finding a current flowing in a circuit at times in a direction opposed to the applied E.M.F. This, however, has also been seen to occur in a circuit containing self-induction, and a much more startling disclosure in a circuit containing capacity is the apparent fact, to be inferred from the curves, that you may have a current in a circuit before you have an E.M.F. to drive it. This, indeed, needs explanation. The explanation is simple; it is that the curves which we have been considering cannot be properly regarded as true of the circuit when the piston is just started, but only after it has been running for some little time. What really occurs at the very start is somewhat complicated, and the reader is referred to mathematical treatises for a consideration of this point. After a very few oscillations matters settle down to the relations indicated in our curves, and we do not need here to consider what occurs at the very start. The state of affairs indicated in our curves is generally summed up by saying that the current is in advance of the E.M F. of the circuit, or in other words that it leads. In the case of the self-induction we have seen that the current was behind the applied E.M.F., and in such cases it is said to lag.

---

[*] *i.e.* to the left on the diagram.

[*] Still assuming a negligible resistance.

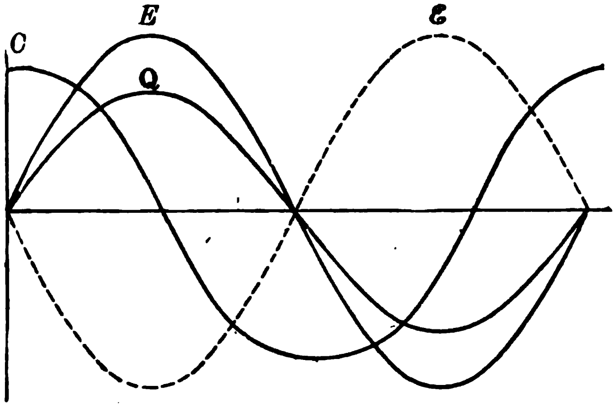


FIG. 322.

It might be as well if at this point we

consider the other hydraulic analogues as depicted in Fig. 321.

R is a vessel filled with pieces of coke, and having a baffle-plate opposite the openings. Suppose R only to be connected to the pump; the pieces of coke would offer resistance to a flow of water by reason of the friction introduced. When the piston is near the bottom of its stroke, its speed is low, and the rate of displacement of water small. Consequently the pressure exerted is small, and therefore the current of water passing through R is also small. The speed, pressure, and current or rate of flow, rise together as sine curves until the maxima are reached, when the piston is in the middle of the cylinder, and then drop again till the piston reaches the top of the cylinder, when the same cycle of operations occurs on the downward or negative stroke. In these circumstances the current is greatest when the pressure is greatest, supposing, of course, the inertia of the water in R is so small that it may be neglected.

Now, suppose L only to be connected to the pump. In this case the mass of water in the pipe is so great that it possesses considerable inertia, opposing corresponding forces to any change of velocity created by the piston. When the piston has reached mid-stroke the velocity is practically constant and, if there be no friction in the pipes, the piston will be exerting no pressure; but when the piston is at the end of its stroke the changes in the velocity of the water are very rapid, and the piston must exert a large pressure against the forces due to the inertia of the water. On tracing these changes carefully we see that the rate of flow is least when the *change of velocity* is greatest and the pressure therefore greatest, while the current (rate of flow) is greatest when the pressure is least, or, in the language of the electrical engineer, the current lags a quarter of a period behind the pressure. This is the exact analogue (*see also* page 14) of a pure self-induction in an electrical circuit.

Next consider all three connected in series as shown in Fig. 321, page 373. When the piston is at the bottom of its stroke the diaphragm of K is distended upwards, and if there were a free outlet on the other side it would tend to pull the piston upwards, so that the piston would have no work to do until it reached mid stroke. As, however, the water leaving K has to be forced through R against a considerable frictional resistance, the piston will have to exert a certain amount of pressure to overcome this friction. Consequently when the current is greatest the piston will exert a certain amount of pressure which will vary with R. That is, R has the effect of reducing the lead of the current as compared with pressure, by necessitating the presence of a pressure in step with current and making the phase relation between the two less than a quarter of a period. If the resistance of R is exceedingly great, the help given the piston by the tendency of the diaphragm to collapse may be very small as compared with the pressure exerted by the piston. In this case, the current being almost entirely due to the pressure of the piston, the pressure and current will be practically in phase.

But we have still the effect of L to consider. Suppose that the effect of R is to reduce the lag of pressure behind the current to half of the quarter period. The inertia of the water in L will tend to throw the pressure forward in phase in its relation to the current, the amount depending upon the magnitude of the inertia. It will easily be perceived that when the inertia is at a particular value the elasticity of the diaphragm will exactly balance it at all stages, and then the piston will be left with merely the resistance of R to overcome, in which case the current and pressure will be in phase. If the inertia is less than this amount the pressure will lag, if greater, the pressure will lead. In this analogue we have worked from a piston moving in a definite manner, producing a definite "current," and have established the pressure relations. In the electrical case it is more usual to consider the application of a definite voltage and deduce the current relations. The results are, however, identical, and the crank diagrams exhibiting the electrical relations are shown in Fig. 324.

MAGNITUDE OF CONDENSER CURRENT.

It is not difficult now to determine the magnitude of the condenser current. If we can settle the height of the crest of one of our sine curves it is all we need do. Obviously the easiest curve to deal with is the quantity curve. If K is the capacity in farads, then $Q = K V$, and therefore, as before, since $V = E_{\text{max.}} \sin. 2\pi f t$ or $E_{\text{max.}} \sin. pt$.

$$\frac{dQ}{dt} = p\, Q_{\text{max.}} \cos. pt = p K E_{\text{max.}} \cos. pt$$

or, $\left(\frac{dQ}{dt}\right)_{\text{max.}} = pK\, E_{\text{max.}}$ (since $\cos._{\text{max.}} = 1$)

thus $C_{\text{max.}} = p\, K E_{\text{max.}}$

As to sign, we need only remember that Q is the quantity in the condenser, and, therefore, when Q is growing the current is flowing *with* the applied E.M.F., and should be regarded as positive.

As to the current here being "wattless," the remarks on page 369, again apply. The E M.F. of the circuit lags very, very nearly 90 degrees behind the current, but there must be a minute component in step with the current, overcoming the low resistance of the wires and condenser plates.

PERMITTANCE REACTANCE.

If, instead of a coil of wire which possesses resistance and inductance, there is in the circuit a condenser so constructed that the resistance of its plates is quite negligible, the circuit has a property not yet dealt with, namely, "permittance." We have seen above that the current flowing in and out of a condenser supplied with an alternating E.M.F. is given by the expression

$$C_{\text{max.}} = p\, K\, E_{\text{max.}}$$

and hence we may say that the E.M.F. necessary to drive one ampere in and out of the condenser of capacity K with the frequency f is

$$\frac{1}{p\,K}, \text{ that is } \frac{1}{2\pi f\, K}.$$

We can clearly treat this voltage as a property of the circuit in the same way that we did resistance and inductance, and since it is convenient to give it a name it has been given the name of "permittance." We also saw that the current in and out of the condenser was 90 degrees in advance of the E.M.F. required to drive it, that is to say, of the E.M.F. required to overcome the back E.M.F. of the condenser; and if we apply these facts to make a vector diagram, we shall get that shown in Fig. 323. Now, it not infrequently occurs that we find a circuit possessed not only of resistance and not only of inductance, but of resistance, inductance, and permittance, and the question at once arises, how are we to calculate the current in a circuit possessed of these three properties when we are given the magnitude of the E.M.F. at work at its terminals? Fortunately the matter is very simple. Let us again consider what happens with a current of one

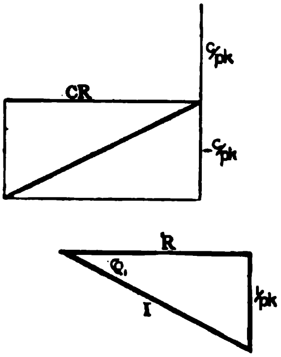


FIG. 323.

ampere. If the current be one ampere we can draw at once three cranks, representing the resistance, inductance, and the permittance respectively, and since the inductance and permittance (Fig. 324A) are exactly opposite to one another, we can perform the operation of algebraic addition at once by graphical means. All we have to do is to shorten the greater of the two quantities by an amount equal to the lesser, as has been done in Fig. 324B. This is equivalent to saying that the permittance voltage precisely neutralises an equal amount of the inductance voltage, which portion may thus be regarded as being inoperative, leaving only the balance or remainder to be considered. The circuit is now reduced virtually to one possessed of resistance and inductance only, or if the inductance is greater than the permittance it reduces to a circuit consisting of resistance and permittance only. As before, we construct a parallelogram with the resistance and what is left of either permittance or inductance, and again obtain a resultant. This resultant is called the impedance of the circuit, whether it be compounded, as at first described, of resistance and inductance, or whether it be compounded of resistance and permittance, or whether, of course, it be compounded of all three as has just been shown. The case just described, in which the voltages required to overcome the three properties of the circuit have really been added vectorially, represents, of course, a circuit in which the three properties may be regarded as acting in series with one another, or we may analyse the circuit and separate its *properties* into three portions, and regard them as being connected in series with one another, as shown in the diagram. It is clear, of course, that when E.M.F.s are in series they must be added, whereas if we have circuits in parallel with one another it is not the E.M.F.s that have to be added to find the total, but the currents. If the circuits are in parallel there is only one E.M.F. operating on all at once, and when they are in series there is only one current flowing through them all at once. Vector diagrams, however, are at our disposal, and serve well for the elucidation of either case. All that is required is a little care in grasping the conditions of the circuit and precisely what is meant by the cranks. If the circuits are in series as above, the cranks represent E.M.F.s. If in parallel they must be used to represent currents.

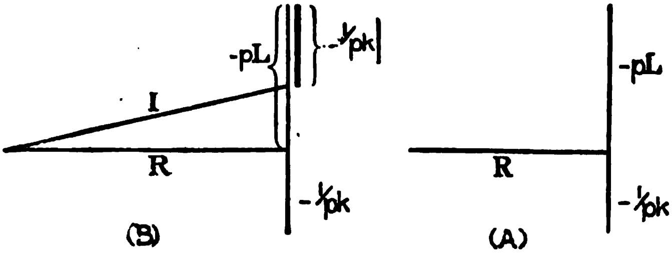


FIG. 324.

CIRCUITS CONTAINING BOTH INDUCTANCE AND PERMITTANCE.

A very obvious inquiry in view of the fact that a self-induction causes a lagging current while a capacity gives rise to a leading current, arises as to whether it would not be possible to so arrange matters that the two effects neutralise one another. If we succeed in doing so it is clear that we shall have had to satisfy two conditions if one effect has to perfectly neutralise the other. We shall first have to see that the amount of lead is precisely equal to the amount of lag, and next we shall have to see that the magnitude of the leading current is equal to the magnitude of the lagging one. In point of fact it is quite easy, not only theoretically, but in practice, to arrange matters so that a self-induction shall be neutralised by a capacity. This is, however, only true in practice when the capacity demanded is not very great, large capacities being not only costly, but difficult, to construct. We have two distinct cases to consider—firstly, the case in which the self-induction and the capacity are in series with one another; and secondly, the case in which they are in parallel.

IN SERIES.

If we connect a non-inductive resistance, a pure self-induction and a pure capacity in series with one another, as in the diagram of Fig. 325, we have a case which is very simple to consider. Before, however, we proceed to its consideration, it may be as well to remark that it is, of course, immaterial in what order the three are connected, although it is impossible in practice to obtain a perfectly pure resistance and perfectly pure self-inductions and capacities. The occurrence of either or both of the other two properties in a portion of the circuit which we have supposed to contain only the third, is of no importance. For the sake of simplicity only have we shown three separate portions to the circuit. It is quite conceivable that an instrument should be constructed or a circuit made up so that the same wire or the same conductor introduces a resistance, self-induction and capacity in the path of the current. In such a case the accuracy of the result would be unimpaired, and indeed, as has been above suggested, every choking coil has some resistance, and practically all the so-called non-inductive resistances have some self-induction. In all common circuits the capacity present is entirely negligible. To return to our diagram: let us suppose a current of C amperes to be flowing through this circuit. This we may represent by a crank of the right length, as is shown at C in Fig. 319. There will then be, if the current flows, five voltages at work, or at least we may consider that there are five voltages, though strictly speaking we can only say that there are three. The five that we will consider are (1) the back E.M.F. of self-induction; (2) an E.M.F. supplied to neutralise this; (3) the back E.M.F. of the condenser; (4) an E.M.F. supplied to neutralise this; and, finally, (5), an E.M.F. to drive the current through resistance. Diagram A (Fig. 326) indicates the existences of Nos. 1, 3 and 5, and their relative positions. Their magnitudes are also written against them in the present case. It is assumed that we have selected a circuit haphazard in which the effects of self-induction and capacity do not happen to balance. As before, the back E.M.F. of the condenser and the back E.M.F. of the self-induction tend to mutually neutralise one another, and hence they of themselves supply at least a portion of the E.M.F.s given above under Nos. 2 and 4. If No. 1 is greater than No. 3, then the circuit will also have to supply an E.M.F. of the same character as No. 3 in order to fully neutralise No. 1; and, on the other hand, if 3 is greater than 1, the circuit will have to assist 1 in order to perfectly neutralise 3. The amount of assistance which, so to speak, has to be given by the circuit either to 1 or 3, as the case may be, is readily determined graphically in the manner shown in diagrams B and C. Diagram B shows p L C preponderating over the $\frac{C}{pK}$ crank, and the difference as shown has to be supplied from the mains, leaving the mains to

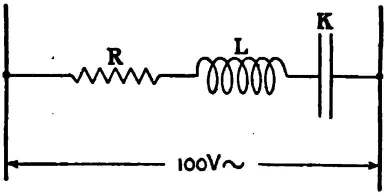


FIG. 325.

supply altogether, when C R is included, the E.M F. indicated at E. In diagram C, $\frac{C}{p\,K}$ preponderates over p L C, with the result that a total E.M.F., as shown at E, has to be supplied from the mains. For brevity it is usual to insert the vectors as has been done in diagram D, thus at once arriving at E without an auxillary diagram. It is now abundantly clear what the relation between the self-induction and the capacity should be for them to mutually neutralise one another. The condition is clearly that $p \text{ L C} = \frac{C}{p\,K}$, for in such case there will be nothing for the mains to supply except C R. It is important, however, to note that the condition for this neutralisation involves the term p, so that any adjustment we may make for a particular circuit in this way will only be correct for one particular frequency, and at any other frequency we shall find that the current lags or leads according as the frequency is raised or lowered. When, however, such an adjustment has been made, the circuit, although it possesses both capacity and self-induction, behaves to alternating currents of the right frequency as though it had nothing but pure resistance. Unless, however, the coefficient of self-induction is small it is an exceedingly difficult matter for all ordinary frequencies to provide a capacity sufficiently large to attain the desired effect. The amount of lag or lead is, of course, shown in every case by the position of the C R crank with reference to the E crank. The current must, as has already been pointed out, be in phase with the component of E.M.F. overcoming resistance. A mechanical analogy is given for this state of affairs on page 382, where resonance is treated of.

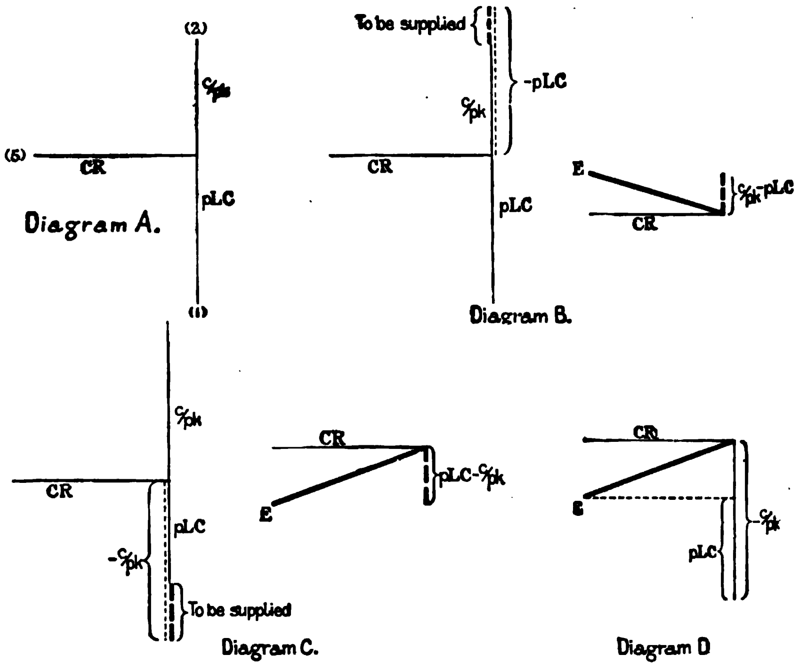


FIG. 326.

IN PARALLEL.

When the capacity and self-induction were arranged in series with one another their function was to produce mutually neutralising E.M.F.s. When, however, they are connected in parallel the E.M.F. at the terminals is the same for both, and is at every instant determined by the E.M.F. of supply; if the two are to neutralise one another it will be in respect of the current flowing; that is to say, they will, if properly proportioned, behave like an infinite resistance. This is to be understood from the following. Let E, in Fig. 327, represent the E.M.F. of supply, and the current that flows through a self-induction possessed of a negligible amount of resistance will be given by the crank C_L, whereas if the E.M.F. supplies a capacity only, the current will be indicated by a crank such as C_K. Now, if the supply is made simultaneously between the same two points to both a self-induction and a capacity as in Fig. 328, we have cranks corresponding to C_L and C_K simultaneously present, and as in the last case we had E.M.F.s neutralising one another, so here we have currents neutralising one another. This will clearly be the case when $C_L = C_K$, and that is when

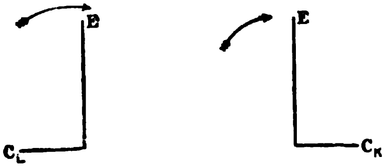


FIG. 327.

$$p\,L = \frac{1}{p\,K}$$

It is well to consider what the physical meaning of this is. The physical meaning is really very simple. It amounts to a circulation, or rather to an oscillation in the circuit formed by the self-induction and capacity, of a current which just keeps time with the pulsations of the E.M.F. in the supply mains. This current oscillating to and fro, as is indicated in the diagram, Fig. 328, gives rise at the terminals T_1, T_2, to an alternating E.M.F. which absolutely coincides in point of time with the E.M.F. of supply. Moreover, it coincides in magnitude so that no current at all from the supply mains can enter this self-contained circuit. It would appear then that the oscillation of this circuit may continue indefinitely; and this is the case, provided always that our assumption of no resistance is true. This assumption has not been explicitly made above, but it has been implied, in that we drew the current, C_L, 90 degrees behind the E.M.F. Now if the current, C_L, is to lag by a full 90 degrees, it means two things: in the first place, that there is no resistance in the circuit, and in the second place that the magnetic field which gives rise to the self-induction is not carried by any material having hysteresis nor by any material in which eddy currents could be generated. Strictly speaking, therefore, it represents a resistanceless coil or solenoid containing no iron or other magnetic material, and not having in its immediate neighbourhood any masses of solid conducting metal. Again the capacity current, C_K, has been drawn a full 90 degrees ahead of the E.M.F., which indicates an assumption of no resistance and no self-induction in the conducting plates of the condenser. This latter assumption is far more closely realised in practice

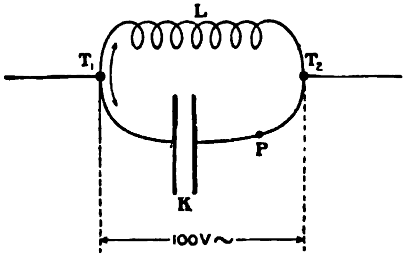


FIG. 328.

than is the former. We further assume no dielectric hysteresis, and therefore no waste of power in the condenser dielectric which is not true of actual condensers except those having air as their dielectric. The failure of any of the assumptions made in regard to C_L or C_K would reduce the angle of lag to something less than 90 degrees, and in that case there would not be perfect neutralisation of currents, but a small resultant would be present, as shown in Fig. 329. This small resultant is not 90 degrees out of phase with the E.M.F., and the vectors therefore represent some power supplied; the power, of course, goes to supply the heat generated in resistance, in hysteresis, and in eddy currents, which, as we have just said, we cannot assume always to be entirely absent. Should they be entirely absent our statement first made above would be correct—namely, that the current will continue to oscillate in that self-contained circuit indefinitely. There being no heat produced, and no loss of energy, an analogy might be drawn between this and the equally impossible case of a frictionless pendulum, making no friction with the air of course, and having no friction in the spring which carries it, oscillating continuously without diminution of amplitude. If we wish to introduce into this analogy the E.M.F. of supply, we can suppose underneath the pendulum a small rocking arm which, when the pendulum was stationary, served to start it swinging, but which rocks to and fro, having precisely the same speed at every instant as that of the pendulum; hence, although the top of the arm swings to and fro with the pendulum bob, it imparts no energy whatever to the bob, since the speeds of the two are identical at every instant, and no force can be exerted by the arm on the bob. The arm thus has no more work to do in oscillating to and fro than if the bob were not present, so also the E.M.F. of supply does in this case, no more work than if the self-induction and capacity were not there.

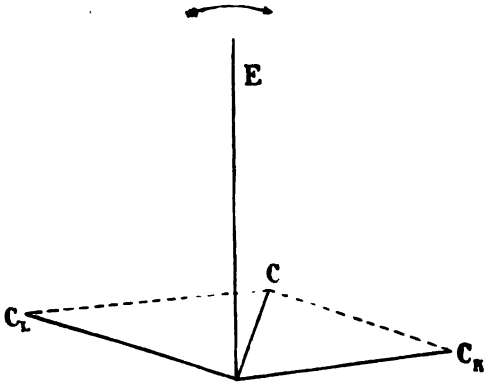


FIG. 329.

If the pendulum tends to slow down (through air friction) it will be subject to a force from the arm, and will receive energy therefrom. This corresponds to the practical electric case, in which the losses, due to resistance, dielectric and other hysteresis, and eddy currents tend to check the oscillating current.

PRACTICAL APPLICATION.

In the year 1891 Mr. Swinburne proposed to employ condensers in the manner just described, in order to cut down the amount of current taken by the primary circuits of transformers during the hours of no-load. Mr. Swinburne had elaborated a peculiar design of transformer which he very appropriately called the "hedgehog." Briefly described, the hedgehog transformer consisted of an open magnetic circuit—that is, a circuit consisting only in part of iron, the rest of the magnetic path being in air. The iron part of the circuit was to all intents and purposes a bundle of iron wires round the middle of which coils were wound, the protruding ends of the iron wires being somewhat bent over. The object of this peculiar design was to reduce the weight of iron in the transformer, and so diminish the no-load losses which, as is shown elsewhere in this book, occur almost exclusively in the iron. Such transformers demand a much higher exciting current, and although this current is, of course, a lagging one, the use of a number of such transformers on the mains would mean a considerable increase in the no-load current carried by them. The increase would be of the order of 50 per cent. over and above the currents demanded by similar transformers of the closed magnetic circuit type, and hence Mr. Swinburne suggested that condensers should be employed to reduce this. The dimensions of the condensers suitable for use in the manner mentioned to reduce the magnetising current supplied from the mains were so very large and the difficulties of construction so great, that the method found no commercial acceptance.

RESONANCE.

The name "electric resonance" has been given to a form of the above phenomenon owing to its close analogy to resonance in acoustics. If we have the electric circuit consisting *entirely* of a self-induction and a capacity connected as in the diagram, Fig. 328, then that circuit possesses what is called a natural period of oscillation, just as a pendulum of given length, or a stretched string, or an organ pipe possesses a natural period of oscillation. In the electrical case the natural period is given by the expression

$$\tau = 2\pi\sqrt{\text{K L}}.$$

In the case shown in Fig. 328 and described above, the natural period of the combination was just the same as the period of the applied E.M.F. If there were no resistance whatever—which we assumed there was not—then if a surging could be started it would *continue* in the circuit with the frequency given by the natural period, even after the source of supply was cut off. For example, if circuit were broken at the point P (Fig. 328) the alternating supply being removed and the condenser charged from an external source in some way, then if the ends of the broken circuit were again united, the first rush of discharge of the condenser would create a field in the coil, and when the magnetic field died down it would charge the condenser the reverse way, and this operation would repeat itself indefinitely: twenty times a second if the periodic time of the circuit were one-tenth of a second. If a further analogy is wanted to convey some conception of the parts played by the capacity and the self-induction respectively, one may regard the combination as being analogous to a flat steel spring, one end of which is clamped tightly in a vice, the other end being loaded with a weight. The stiffness of the spring will correspond to the capacity of the condenser, or rather, inversely to that capacity, so that a stiff spring will represent a condenser of small capacity, while a condenser of larger capacity will be represented by a weaker spring. The moment of the weight loading the free end of the spring corresponds to the inertia or self-induction of the circuit, the moment of inertia of the weight and the coefficient of self-induction being true analogues. Such an arrangement would have a natural period of oscillation, and if the free end of the spring be pulled to one side and then released, the weight would wag to and fro at a definite rate, the rate being obviously dependent upon both the stiffness of the spring and the mass of the weight. The spring *bent to one side* represents the condenser *charged one way*, and the velocity of the weight represents *rate of flow* of electricity, *i e.* current strength. Now we may clearly treat this mechanical combination in two ways. We may, on the one hand, take hold of it firmly at the free end and pull it to and fro at any rate which pleases us, but not necessarily at a rate which pleases the combination, if we may use such an expression. There is only one rate which "pleases" the combination, that rate being, of course, its own natural rate, and if we take hold of the weight and pull it to and fro at any other rate of vibration, we impose upon the system what is called a forced rate of vibration.

On the other hand, we may, if we are careful, supply impulses to the system which are carefully timed to agree with the rate of free vibration, so that whenever the weight is tending to move in one direction or the other, we are pushing or pulling it so as to help its natural tendency. The result of such treatment will be to increase the total amount of swing every time, and the swing will, therefore increase more and more until the spring breaks. Resonance occurs in an electrical circuit then if the natural period of oscillation of circuit, comprising a condenser and a self-induction, happens to agree precisely with the frequency of the impulses imparted to it by the alternating E.M.F., the source of supply, the condenser and the coil being all in series (not as in Fig. 328). It is, of course, quite a remote contingency that such a coincidence of frequency should occur very precisely, but it is not necessary for it to occur with great precision, since dangerous conditions arise if there be only approximate correspondence between the two frequencies, namely, the frequency of supply and the natural frequency. We might take as an example the case of a small high-voltage alternate-current generator designed for testing cables. The test is to take place on the dielectric, and the cable is for this purpose coiled in a tank of water, the two ends of the cable only standing out of the water. These two ends are carefully insulated, and one terminal of the alternator is connected to the copper, while the other terminal is connected to the water in the tank. Thus, when pressure is applied the whole of the dielectric is subjected to alternating stresses, and the arrangement simply becomes a condenser, of which the cable insulation is the dielectric, the copper of the cable is one coating, and the water in the tank the other.

Now the armature of the alternator possesses self-induction, and hence when the armature is connected to the cable the two have, as has been remarked above, a natural period of oscillation. It will be as well to give figures in this connection, and we will therefore suppose that the alternator armature has a coefficient of self-induction of 0·6 henry, while the cable has a capacity of 2·4 microfarads. The natural period of this combination is easily computed as 0·00754 of a second, and if, therefore, the alternator supplies the circuit with about this frequency, dangerous conditions will assuredly arise, and we shall have a breakdown. So far, however, nothing has been said as to how the condition may be dangerous, or why a breakdown results, except in the mechanical analogue, when it was stated that the swings would get greater and greater until the spring was broken. This assumed, in the mechanical case, that there was no friction of any kind; but, of course, although the friction may be small and of little importance for small swings, it becomes of considerable importance when large oscillations are taking place. The air friction, for example, at the centre of the swing, is a matter not to be neglected when the swings get very large; so, in the electrical case, the resistance of the various portions of the circuit may be small and unimportant for ordinary work, but when resonance occurs the resistance is the only thing which limits the oscillations, which apart from it would theoretically rise to an infinite magnitude. We saw, however, on page 378, that the effect of a self-induction and a capacity in series with one another was, if they were properly proportioned, to wipe one another out, and if an examination is made of the proportions which were then pointed out as being suitable, it will be seen that they are the very proportions which obtain when resonance is occurrent. In fact, we were in the former paragraph dealing with resonance in one of its forms.

Let us apply the results then obtained, namely, that the self-induction and capacity neutralise one another, to the present case. Taking the figures given above, and supposing that the armature has a negligible resistance and the cable a resistance of 2 ohms, we get the following results :—

$$pL \text{ must be equal to } {}^1/_{pK}$$

$$p^2 = \frac{1}{2\cdot4 \times \cdot6 \times 10^{-6}} = \frac{10^6}{1\cdot44}$$

$$\therefore 2\pi f = \frac{10^3}{1\cdot2} \text{ and } f = 132\cdot5.$$

That is to say that if the alternator runs at a frequency of 132·5, the whole of its E.M.F. will be at liberty to cope with resistance only, and we have the result $C = E/R$. Now if $E = 5{,}000$ volts, as it well may for such tests, the current appears to be 2,500 amperes. We say "appears to be" advisedly, for the following reason : if the current did rise to 2,500 amperes the voltage at the terminals of the cable and alternator would be $p\ L\ C$ or $\frac{C}{pK}$, either expression giving the same result, of course, viz. 1,252,000 volts. This would never be reached, as the cable or alternator would simply break down first. If we enquire whence would come this huge force, the answer is that it comes from the synchronism of the impulses with the natural surgings, and corresponds to the force above described which breaks the spring in the vice. The effect of running at other frequencies may be calculated easily. If, for example, a frequency of 100 per second were supplied, p L becomes 376·9, $1/p$ K is 664, impedance is 287, and the current about 17·4 amperes. The voltage at the generator terminals would be about 6,560 volts, and across the cable dielectric about 11,600.

CHAPTER III.—CALCULATION OF ALTERNATING VALUES.

VIRTUAL VALUES OF ALTERNATING CURRENTS—VIRTUAL VALUES IN CLOCK DIAGRAMS—APPLICATION OF CLOCK DIAGRAMS TO SOLUTION OF PROBLEMS—PARALLEL CIRCUITS—WATTMETER ERROR.

VIRTUAL VALUES OF ALTERNATING CURRENTS.

A DECISION of very great importance in connection with the alternating circuit has now to be considered. We have to decide precisely what is the value of a continually changing current when compared with a continuous current. If a man's income varied continually throughout the year, being nothing for the month of January, £10 for the month of February, £20 for March, and so on up to June, and then decreasing till it was nothing again for the month of December, it would be an extremely simple matter to determine what the annual income of that man was as compared with that of a man whose income was unvarying. If, on the other hand, two men whose incomes are to be compared are supposed to be engaged in an occupation such that the value of each £1 of income depended on the income itself, it would not be quite so simple. Suppose, for example, that an income of £10 in February was of less value to the man (say for speculative reasons) than *the same* income in March, and that the money would be even more valuable in April, and so on, so that the actual value of a given sum varied throughout the year in exactly the same way as the man's income for the time being varied. In order to estimate properly the relative value of these two incomes we should have to go into a careful calculation. We have a very similar consideration to make in determining the relative values of an alternating and a continuous current. The value of a current to an engineer is, of course, the power associated with it, and it will be remembered that in the case of a continuous current the power is proportional to the square of the current strength ; in a word, that it was represented by the quantity $C^3 R$. Now the only basis for the proper comparison of an alternating and continuous current is that of the power represented by each in combination with similar E.M.F.s ; hence what we have to compare is the total work which will be done in a given resistance by a continuous current of a given value in say, one second, with the total work that will be done by an alternating current of equal maximum value in the same time. The two cases are clearly shown in Fig. 330 for a current of one ampere. Most alternating currents oscillate from fifty to one hundred times a second, so that if we are to draw the current for one second in our figure we shall have to show fifty to one hundred ripples. Clearly, then, it will be inconvenient to show the current for a whole second, and since all the ripples are exactly alike it will be far better to take the current for one-fiftieth or one-hundredth of a second, so confining our attention to one complete ripple. Then, since all subsequent ripples are exactly like it, we have all the information we want. We have, however, to compare the work done in a given time, or the power represented by the flow of these two currents through the resistance, and this, we have seen, depends upon the squares of their values. We must, then, square these values at every instant of time, and if we do this it is clear that the straight line representing the continuous current will give us another straight line, for the square of its value gives us only one result. The full horizontal line, then, marked "+ C or + C² (direct)," will represent either a direct current of one ampere or that current squared. The squares of the alternating current values will depend at each instant on the corresponding values of the current, and since the square of a negative quantity gives us a positive quantity, a little reflection will show that the curve of squares of the alternating current is that shown by the wavy line marked C²∿.

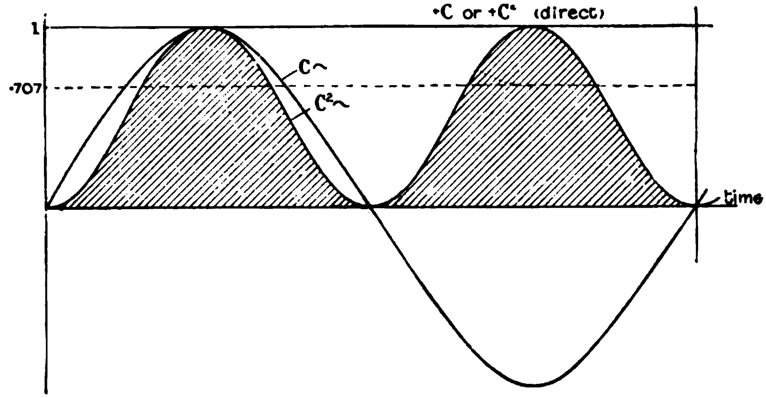


FIG. 330.

Here, again, the reader cannot be too strongly urged to do this for himself. Let him construct a curve of sines as was advised on page 355, and let him make the length of his crank one inch, so that the height of the crest of his current ripple or wave will be one inch above the horizontal line; and, finally, let him evaluate C² at numerous points, and plot the curve of C². We now reason thus:—The work done in one-fiftieth of a second by means of either current is measured by C² × *t*: that is, by the area under the C² line. A glance at the diagram at once shows that the shaded area under the alternating C² is only half the total area under the direct C², for the unshaded wavy area is just the same as the shaded, and these two are both included under + C². Hence the work that can be done with a direct current of one ampere is double that done by a sinusoidal alternating current whose ***maximum*** is one ampere. Or we may say

$$\sim C^2 t = \tfrac{1}{2}\,(\text{direct } C^2) \times t,$$

therefore ∿ C corresponds to $\frac{1}{\sqrt{2}}$ C (direct).

It follows then that an alternating current with a maximum value of one ampere only does as much for us as a direct current of $\frac{1}{\sqrt{2}}$ or 0·707 ampere. The name given to this value of an alternating current is "virtual value," so that all virtual values (if sine curves) are 0.707 times the maxima. The names "effective" and "R.M.S." (meaning "root mean square") will also be met with.

The student may urge that the above reasoning only holds good for currents of one ampere, but he will see that this is not so, for it is after all only a question of scale. The same diagram would have done for a comparison of two currents (direct and alternating) of two amperes each, only we should have wanted double the scale for the currents, and four times the scale for their squares. If such scales were used there would be no difference between that diagram and the one we have given.

In our clock diagrams we have hitherto always made the lengths of our cranks represent maximum values. Here again it is merely a matter of changing the scale if we wish to make them represent virtual values. Since all measuring instruments are calibrated to read virtual values, and since we never need to deal with other than virtual values (except for analytical work, as when tracing out certain phenomena), we may at once make all our cranks stand for virtual values, and use the diagrams *as they are*, entirely unaltered. If a coil is traversed by a sinusoidal field, L is its coefficient in *virtual volts;* and if E is virtual volts, then the current

$$C = \frac{E}{\sqrt{R^2 + p^2 L^2}} \textit{ virtual } \text{amperes.}$$

Also, if we have C virtual amperes at E virtual volts, the watts will be C × E × cos. ϕ.

The presence of the 2 in the denominator of the expression for watts on page 366 is now explained. There we had $E_{max.}$ and $C_{max.}$, and each is to be divided by $\sqrt{2}$ to get virtual values; hence their product is divided by 2.

VIRTUAL VALUES IN CLOCK DIAGRAMS.

In all the clock diagrams given in the last chapter the lengths of the cranks were used to indicate the maximum values of the various quantities.

CLOCK DIAGRAMS APPLIED TO PROBLEMS.

One of the most useful applications of clock diagrams is to the evolution of the magnitude and phase of a current flowing in a complex circuit where the applied E.M.F. is known and the details of the circuit given. The more difficult cases arise when parallel (branched) circuits have to be dealt with, and these will be considered when the series cases have been discussed more fully than on page 378.

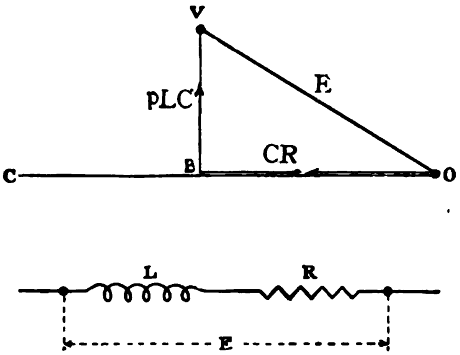


FIG. 331.

In the first place it is well to emphasise the facts that all supplied voltages overcoming mere resistance must be drawn in phase with the current; that those overcoming pure self-induction must be drawn at right angles to the current crank and *ahead* of it, and that those supplied to overcome the effect of a pure capacity must be drawn 90 degrees *behind* the current crank. Further, it is well to point out again that it is impossible to distinguish between two pure properties acting in series with one another and a combination of the two in one wire. In the following diagrams the summation of vectors will not be made by drawing parallelograms and inserting the diagonal, but by the usual method of adding line to line, having due regard to direction and sense. Thus, in Fig. 331, the resultant E.M.F., O V, is obtained by drawing the line, O B to represent C R, and then from the point, B, drawing at once, and so adding, the line B V to represent p L C, giving O V as the sum or terminal E.M.F. across the R and L indicated below the vectors. In Fig. 332 a circuit consisting of eight portions, all in series, is shown, and above it the appropriate diagrams. The left-hand one of these shows how the terminal E, across the whole circuit, may be arrived at by taking each circuit property in succession, while the right-hand one shows that the same result is obtained (for the circuit *as a whole*) by considering all the resistances to be placed together and all the self-inductions together. This serves further to illustrate the identity of result when a coil possessing both resistance and inductance is regarded, for graphical work, as a coil of pure inductance in series with a wire of pure resistance. Moreover, it must be clear that the results are identical whether inductance voltage is added to resistance voltage or vice versa, so that in a circuit containing several portions all in series the terminal E.M.F. is unaffected by the order of their arrangement. Figs. 333 and 334 are self-explanatory, indicating, as they do, the procedure of addition when the impedance of the circuit contains a capacity effect. In Fig. 333 this latter is greater than the effect of self-induction, while the reverse condition obtains in Fig. 334. The addition in Fig. 334 has been effected in two different orders.

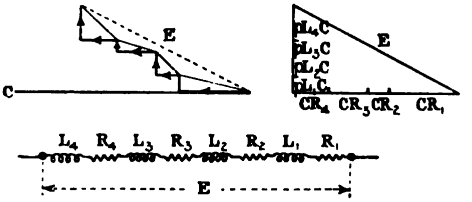

E
C
pL_4C
pL_3C
pL_2C
pL_1C
E
CR_4 CR_3 CR_2 CR_1
L_4 R_4 L_3 R_3 L_2 R_2 L_1 R_1
E

FIG. 332.

The order shown in the lower part is preferable, since the addition $-p$LC and $-$ C/pK may be done directly, algebraically if need be

The algebraical result is easily seen to be

$$E = \sqrt{C^2 R^2 + \left(p\,LC - \frac{C}{p\,K}\right)^2}$$

$$= C\sqrt{R^2 + \left(pL - \frac{1}{p\,K}\right)^2}$$

Thus the expression for impedance given on page 371 must be amplified if permittance be present by combining it with the inductance, as is done by the terms in the bracket. If there be any number of pure or combined resistances, permittances, and inductances *all in series*, they may be arranged in three groups and *all* the resistances included in R, *all* the inductances in p L, and *all* the permittances in $\frac{1}{pK}$. This grouping having been effected, the

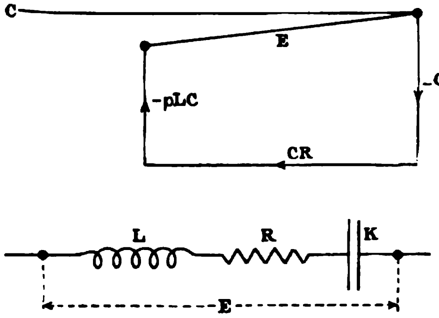


FIG. 333.

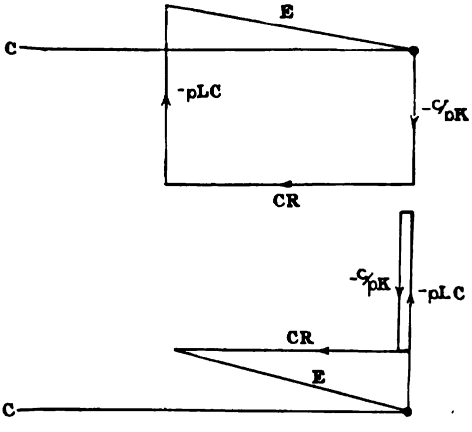


FIG. 334.

current passing under a given E.M.F. is at once determined by the result

$$C = \frac{E}{\sqrt{R^2 + \left(pL - \frac{1}{pK}\right)^2}}$$

One example will suffice. If a coil whose L is 0.00318 henry, whose R is 0.1, be in series with a wire of 3·8 ohms resistance and of L = 0·0000636, and with a condenser of 756 microfarads (0·00756 farad) whose coatings have a resistance of 0·1 ohm (Fig. 335) we calculate the following values for a frequency of 50 periods and a supply voltage of 100 volts :—

Total L = 0·003816. Total $pL = 1·2$.
Total R = 4. $\frac{1}{pK} = 4·2$.

$$\text{Impedance} = \sqrt{4^2 + (1·2 - 4·2)^2}$$
$$= \sqrt{16 + 9 = 25} = 5.$$
$$\text{Hence current} = \frac{100}{5} = 20 \text{ amperes.}$$

PARALLEL CIRCUITS.

Parallel circuits exhibit considerable complexity when treated analytically, but readily yield to graphical treatment though they are less simple than the series. The key to the solution of this type of problem lies in the fact that the E.M.F. at work at the terminals of all branches is the same, and that each branch may therefore be treated independently, and its current determined as regards magnitude and phase relation to the E.M.F. The solutions so obtained may then be combined in one diagram and the currents compounded to give the total resultant. This method neglects any effects of mutual induction between the parallel branches; the consideration of such effects is outside the scope of this book and the reader is referred to advanced mathematical treatises on the subject.

The precise method of combining the individual diagrams into one must be determined by ease and convenience of manipulation. The partial or entire elimination of calculations also affects the graphical method somewhat. If we consider the case of three parallel circuits, $L_1 R_1$, $L_2 R_2$ and $L_3 R_3$ as indicated in Fig. 336, we may proceed variously; for example, (1) construct to any convenient scale three impedance triangles, which will give the angles O_1, O_2 and O_3. The only calculation required for this is pL for each branch. (2) A line OE is drawn to some scale to represent the voltage E at the terminals of each circuit. (3) The angles, ϕ_1, ϕ_2 and ϕ_3, are then transferred to the lines V_1, V_2 and V_3, and a semicircle described with OE as its diameter. The length of the lines, OV, cut off by the semicircle, give *to scale* the voltages at work overcoming resistance in the respective circuits. (4) Divide these lines, V_1, V_2 and V_3, by the resistances, R_1, R_2 and R_3, respectively, and cut off (or produce) lengths, OC_1, OC_2, OC_3, to any convenient scale for the quotients obtained. (5) Compound C_1, C_2 and C_3, in the usual way, and so obtain C, which is the whole current flowing in the main ammeter, both in phase and magnitude. The *rationale* of the third and succeeding steps is as follows. Since the values of I_1, I_2, I_3, are unknown to begin with, we cannot readily construct the three triangles with their hypothenuses all parallel: if we could they might be constructed upon OE at once, and the transference of the angles avoided, so shortening the graphical manipulations.

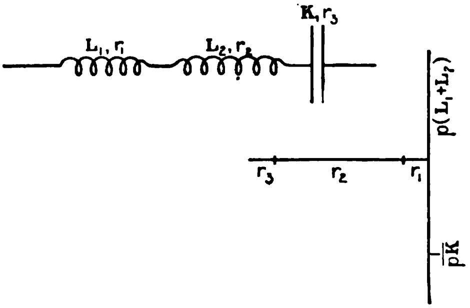


FIG. 335.

The transference of the angles, ϕ_1 ϕ_2 and ϕ_3, gives at once the phase of the current cranks relatively to OE, but not their magnitude. An impedance triangle is always necessarily a right-angled triangle, and if each side is multiplied by C, it gives (*see* page 372) a voltage triangle for the circuit. Since the total voltage is the same for each circuit, and is OE, it follows that OE is the hypothenuse of three triangles, of which each will have also one side lying on the appropriate line, V_1, V_2 or V_3. The complete triangles then may at once be determined by the semicircle on OE, for three right-angled triangles may be drawn by joining E to each point where the semicircle cuts, OV_1, OV_2, OV_3. But OE is the terminal voltage *to scale*, and therefore EV and VO are the voltages overcoming self-induction and resistance respectively also *to the same scale*. The lines EV are useless and omitted. Now that we can scale off the voltages expended in resistance for the three circuits, the values may at once be divided by corresponding resistance, and the current evaluated. It remains, then, merely to choose a current scale, and to mark off the lengths, OC_1, OC_2, OC_3, to that scale, and so exhibit on the diagram the relative magnitudes and phases of the currents in the three circuits in question. By compounding these we must obviously arrive at the true vector sum or total current supplied, and the phase angle, ϕ, between this and the terminal voltage.

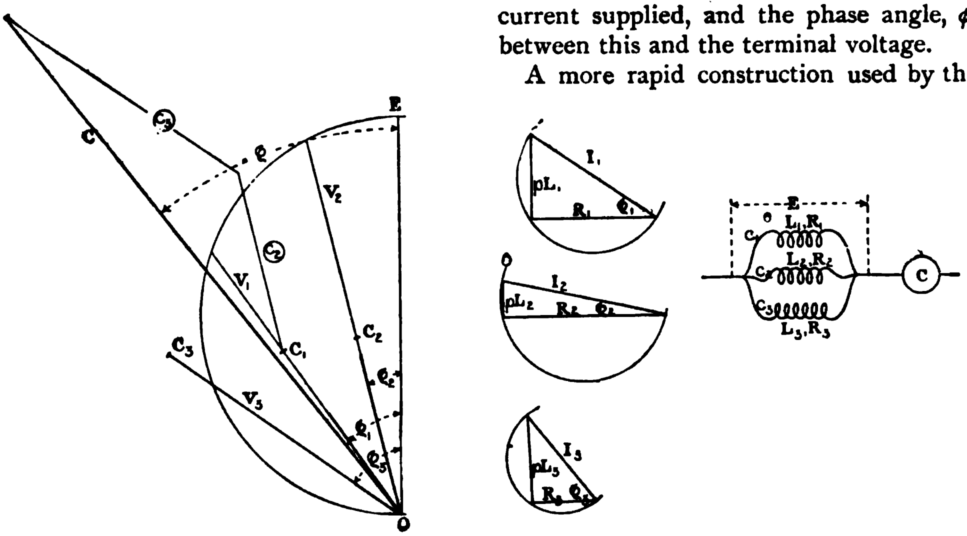


FIG. 336.—VECTOR DIAGRAMS FOR PARALLEL CIRCUITS.

A more rapid construction used by the author is that shown in Fig. 337*a*. A vertical line, marked pL at the top and $\frac{1}{pK}$ below, is drawn of a sufficient length to allow of a convenient scale of ohms, and a line marked R cuts the other at right angles. Along these lines are marked off to scale the inductances, permittances, and resistances of the various parallel circuits, and the points numbered to avoid confusion. Similarly numbered points are then joined by lines which give the impedances of the respective branches and their angles of lag. These lengths are then measured and, some one of convenient length having been selected as a unit, the others are expressed in terms of their *inverse* proportion to that one. A polygon is then formed, just like a polygon of forces, but that each side is of a length inversely proportional to the impedance to which it is parallel. Each side thus represents the proportional value and angle of the current through the corresponding impedance. The line closing the polygon gives the total current and angle of lag ϕ in the main circuit, the R line giving the direction of the impressed voltage. The circuits shown in Fig. 337*b* have been dealt with in this manner in Fig. 337*a*. The values employed are given in the accompanying table. The last column gives the inverse proportion of each impedance in terms of the first (the one selected as standard for current scale) and also, under *l* the proper length for the link in the polygon.

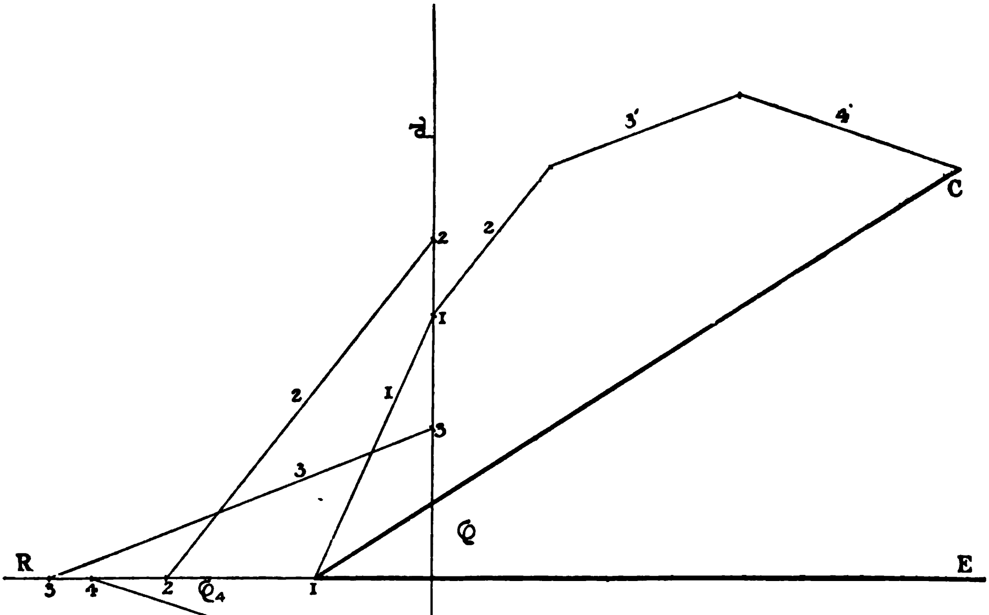


FIG. 337*a*. — VECTOR DIAGRAM FOR TOTAL CURRENT SUPPLIED TO BRANCHED CIRCUIT.

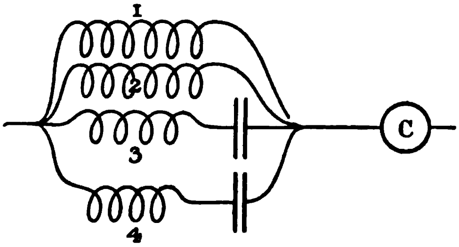


FIG. 337*b*.

The scale employed in the diagram is 1 cm. = 1 ohm. The values of *l* are very quickly read from a slide rule by reversing the slide end for end and setting it so that the value of the impedance selected (as standard for current scale) is seen on the slide in line with the *same number* on the *corresponding* scale of the rule. The fractional values are not wanted in ordinary work, but

Circ.	R	pL	$1/pK$	I	C. (prop.) and *l*.	
1	1·55	3·5	0	3·8	1	3·8
2	3·5	4·5	0	5·7	0·666	2·53
3	4·95	2·9	0·92	5·35	0·71	2·7
4	4·5	0·5	2·0	4·75	0·8	3·04

are given in the table to make the process clear. Thus, in the example given, 3·8 on the top edge of the slide was in line with 3·8 on the lower scale of the rule. By moving the cursor now to 5·7 on the rule 2·53 is read (upside down, of course) on the top edge of the slide, and on moving it to 5·35 on the lower scale, 2·7 is obtained on the slide and so on. The whole operation takes much less time to perform than to read off. Of course, if widely differing values are present the upper scale of the rule and lower edge of the (inverted) slide may have to be used at a slight sacrifice of accuracy. The table having been drawn up and filled in, the polygon is drawn, using impedance No. 1 as the first link; 2′ is drawn parallel to 2, but 0·666 times as long as 1, viz., 2·53 cm. The lines 1, 2′, 3′, and 4′ show the currents in each branch, and C shows the total current supplied, but the scale for current has not yet been explained. The line 1 represents the current in the circuit whose impedance is 3·8 ohms, hence the terminal voltage must be divided by 3·8 to determine the current scale. If the voltage be 50 the current in that branch is 13·15 amperes. The closing link C is 10·1 cm. long, and therefore represents a current of $13{\cdot}15 \times \frac{10{\cdot}1}{3{\cdot}8} = 34{\cdot}8$ amperes. The angle marked ϕ is clearly the angle and not the angle R 1 C, for a glance at one of the impedance triangles, No. 4, for example, shows that the angle marked ϕ_4 is the correct one. A most useful application of the principles involved in the construction of these diagrams is to be found in the following method of evaluating the

ERROR IN A WATTMETER.

The character of this has already been indicated on p. 294, but the magnitude now remains to be calculated. It must be borne in mind that, while the wattmeter is required to measure EC cos ϕ, and should do so by the mutual reactions of two currents, one in a fine wire coil and the other in a thick wire coil, the current in the thin wire coil is not in phase with E, but lags behind E by an angle θ (Fig. 338), determined by the time constant of the winding. The forces between the coils causing the deflection are therefore proportional to the currents in them, multiplied by the cosine of some unknown angle, ϕ'. Moreover, the current in the fine wire coil is less than when calibrated with continuous current, owing to the inductance of the fine wire circuit. Thus, in Fig. 338, if OE represent the E.M.F. at the terminals of the circuit whose power is to be measured, and OC represent the current in that circuit, we can find the relative value of the current in the fine wire coil as compared with that which flows under the same continuous voltage by constructing the voltage triangle, $R_f c$, $pL_f c$, so obtaining the point E′. OE′ is the voltage in phase with the fine wire current, so that $\frac{OE'}{R_f} = c$, where R_f and c are the resistance and current in the fine wire circuit. With continuous current, however, the value of c was $\frac{OE}{R_f}$. The read-

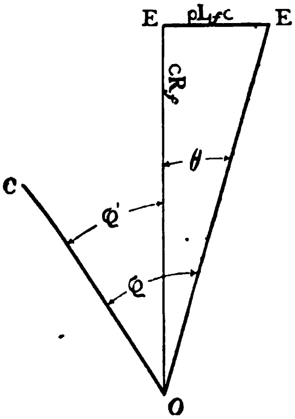


FIG. 338.—DIAGRAM OF WATTMETER ERROR.

ings are therefore now too low in the ratio of $\frac{OE'}{OE}$ and this ratio is fixed for the given frequency, which gave the value of pL_f used. The other cause of error is, under the conditions shown, of the opposite kind, and tends to make the reading too high, since cos E′OC is greater than cos EOC, and the wattmeter reads

$k \times OE' \times OC \times \cos E'OC$ instead of
$k \times OE \times OC \times \cos EOC$

where k is a constant depending only on the dimensions of the coils and control. The second correction, then, is in the ratio

$$\frac{\cos EOC}{\cos E'OC} = \frac{\cos EOC}{\cos (EOC - EOE')}$$

but $\cos EOC = \frac{R}{\sqrt{R^2 + p^2 L^2}}$ where R and L are the values belonging to the circuit being tested. Also

$$\cos EOE' = \frac{R_f}{\sqrt{R_f^2 + p^2 L_f^2}}.$$

By expanding cos (EOC — EOE′) and substituting the values given above, we have for the correcting factor of the second kind

$$\cfrac{\cfrac{R}{\sqrt{R^2 + p^2 L^2}}.}{\cfrac{R}{\sqrt{R^2 + p^2 L^2}} \times \cfrac{R_f}{\sqrt{R_f^2 + p^2 L_f^2}} + \cfrac{pL}{\sqrt{R^2 + p^2 L^2}} \times \cfrac{p L_f}{\sqrt{R^2 + p^2 L_f^2}}} \quad \text{(b).}$$

The ratio of $\frac{OE}{OE'}$, correcting the first-mentioned error, is $\frac{\sqrt{R_f^2 + p^2 L_f^2}}{R_f}$ (a), and by multiplying the two correcting ratios (a) and (b) we have

$$\frac{R (R_f^2 + p^2 L_f^2)}{R \times R_f^2 + p^2 L L_f R_f} = kk_1,$$ where k_1 is the numerical quantity by which the reading obtained must be multiplied to give the true watts.

It was pointed out above that in the case represented by the diagram, the two errors were opposite in character. It is therefore conceivable that under suitable conditions they might be equal, and so cancel one another. This is indeed the case, and when the angles E O E′ and E O C are identical, the factor k_1 is unity. This can be proved by making $\frac{p\,L}{R} = \frac{p\,L_f}{R_f}$ in the expression. If the conditions are as shown in Fig. 338, the second error preponderates, and the wattmeter reads too high and k_1 is less than unity; if the angle, E O C, the ϕ of the circuit under test, is less than θ, then the wattmeter reads too low and k_1 is greater than unity.

CHAPTER IV.—POLYPHASE.

INTRODUCTION—DISTRIBUTION LINES—LINE VOLTAGES AND LINE CURRENTS—THREE-PHASE—MEASURMENT OF POWER IN POLYPHASE CIRCUITS.

For reasons which are dealt with in the following section of this book, where alternating current generators are described, there is necessarily a considerable amount of unoccupied space in that portion of a single-phase generator which carries the armature windings. Briefly stated, the reasons may be summed up by saying that in order that the windings may be the seat of an alternating E.M.F. of sinusoidal shape, they have to be spaced so far apart as to leave considerable portions of iron in the armature unoccupied. This was appreciated a very long time ago by the late Mr. J. E. H. Gordon, who accordingly constructed for the Great Western Railway some generators in which this ordinarily unoccupied space was filled with a second set of windings. By this means Mr. Gordon succeeded in compressing into one machine the parts which would have been necessary in two generators to give the desired output, within much smaller limits of space and weight, by assigning to the two sets of windings on the one machine the respective functions of the two generators that would otherwise have been employed. Owing, however, to the fact that the second set of windings occupied the gaps left between the undividual coils of the first set of windings A, the currents produced in the windings B—although identical in voltage, in frequency, and in wave form with those in A—were not in step with the currents generated in A. This will be obvious on a little reflection when it is considered with reference to Fig. 339 that the coils A are threaded by the maximum flux at the moment shown in the diagram, while the coils B are not threaded by any flux whatever, and that a moment or so later, when the poles have moved forward a little, the reverse condition of affairs holds good. It must be clear, then, that at any particular moment the E.M.F. in coils A will be a quarter of a period out of step with the E.M.F. in the coils B, since the time occupied by one period is the time that elapses between the presentation of a north pole to one coil and the next presentation of a north pole to that same coil. The upshot of all this was that the two circuits, A and B, served by one of Mr. Gordon's generators were kept entirely independent one of the other. Other inventors as well as Mr. Gordon experimented with currents having the mutual relationship of those in A and B, and, doubtless, had Mr. Gordon

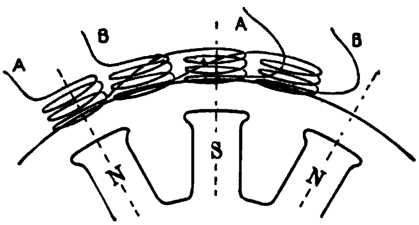


FIG. 339.—TYPICAL ARRANGEMENT OF COILS ON A TWO-PHASE GENERATOR.

lived longer, he would have done valuable pioneer work in this direction. It remained, however, for others to show that if the two currents thus generated are fed into the windings spaced round a ring in the manner shown in Fig. 340, the net result in the space enclosed by the ring will be that of a rotating field. Limitations of space forbid the description here of the various steps by which men whose names are at present household words among electrical engineers arrived at the application of these currents to the purposes about to be described, and for a most complete and interesting account of these the reader is referred to Dr. S. P. Thompson's work on polyphase electric currents, especially the earlier editions.

In order to see how a rotating field is produced, let us consider step by step what goes on in the coils of windings and in the iron ring depicted in Fig. 340. The currents supplied to the two windings, A and B, have the mutual relationship indicated in the curve, Fig. 341, and in Fig. 342 is given a series of diagrams illustrating the electric and magnetic conditions at sixteen successive stages in one period. From these it will be seen that the fields produced by the coils, A and B, combine to produce one field whose general direction moves by successive stages within the circle of the ring, so as to apparently revolve continuously in a clockwise direction, and the student who is for the first time considering this relationship is strongly recommended to scrutinise the diagrams given in Fig. 342 very closely, in order that he may thoroughly grasp all that is involved. It will be seen that the twelve stages are shown in two columns of six each, and that each stage is represented by three steps of construction, arranged in line horizontally. On the left of each stage are shown the two rotating cranks, A and B, always at right angles to one another, but occupying varying positions corresponding to the changes of phase as the period is completed. On the right of the vectors are vertical lines, projections from the cranks, which give the instantaneous values of the currents in the two phases, corresponding to the phase of the cranks: vertical lines drawn above the level of the centre of rotation of the cranks are treated as positive and those below as negative. The third step in the construction on the right shows the field produced by each current A and B and the resultant field due to the combination. Glancing at Fig. 340 the reader will see that phase A would produce a field in a vertical direction across the inside of the ring and phase B one horizontally across. These directions are adhered to in Fig. 342 and when the

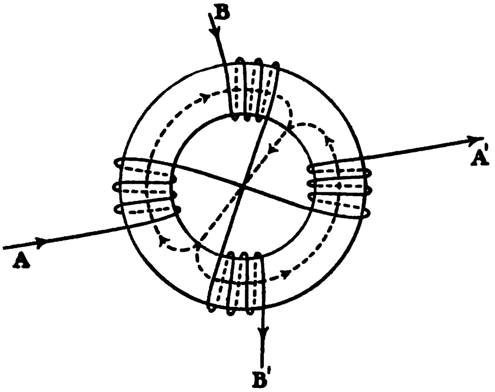


FIG. 340.—RESULTANT FLUX IN RING SUPPLIED WITH TWO-PHASE CURRENT.

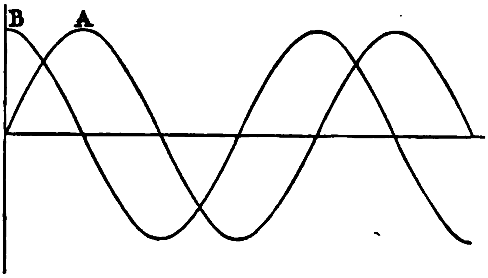


FIG. 341.—CURVES ILLUSTRATING MUTUAL RELATIONS OF TWO-PHASE CURRENTS.

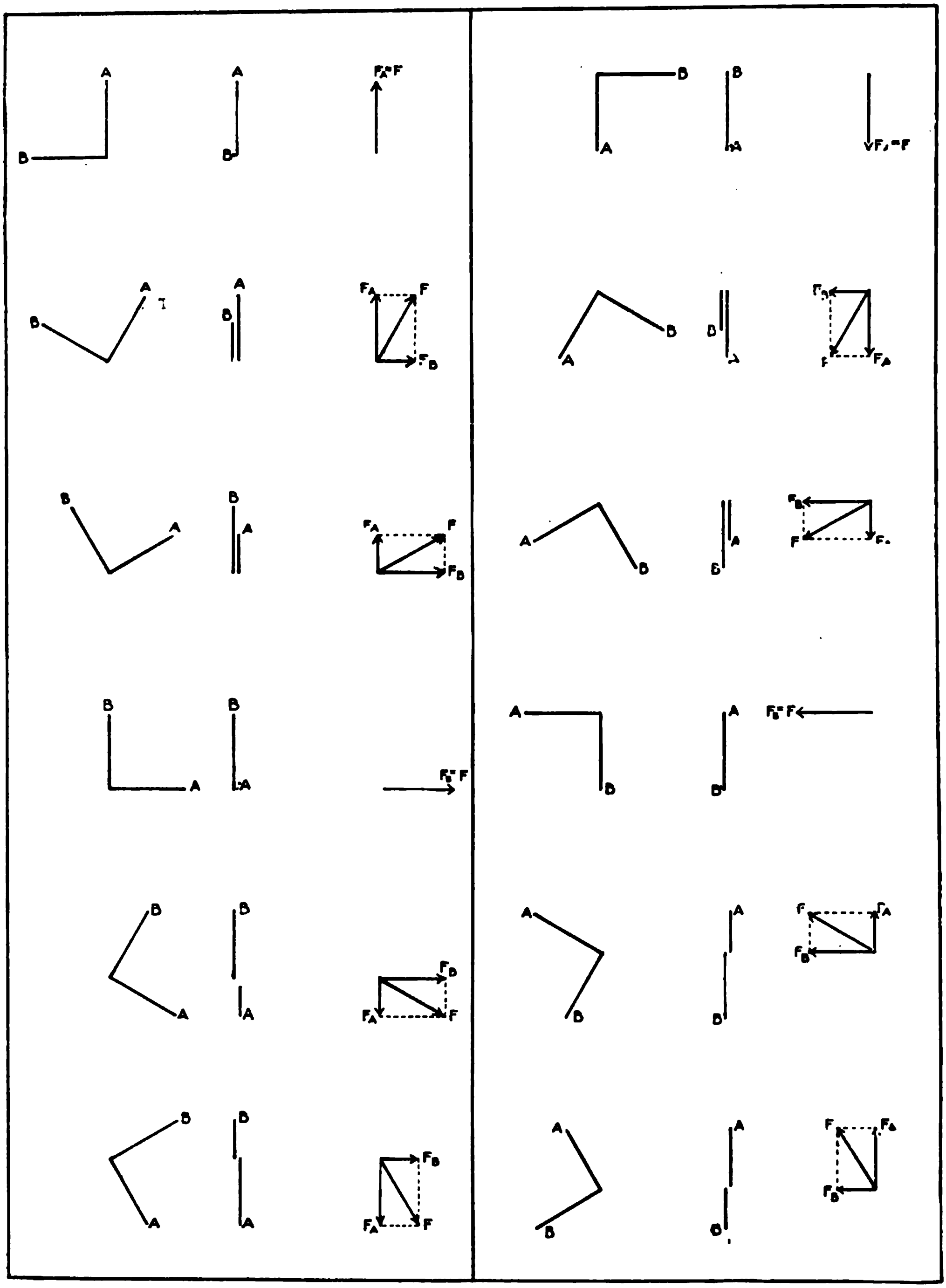


FIG. 342.—DIAGRAMS ILLUSTRATING SEQUENCE OF THE CURRENT CHANGES AND THE RESULTING FIELD PRODUCED BY THEM IN A RING SUCH AS IS SHOWN IN FIG. 340.

current in A is positive the field is supposed to have an upward direction, and if negative a downward direction: when current B is positive its field is from left to right, and when negative from right to left. In the first stage (top of the left-hand column) current B is 0 and is represented by a dot, and again in the tenth: A is so shown in the fourth and seventh stages. The component fields are marked F_A and F_B respectively, and the resultant field is marked F. The progressive stages of rotation of F are clearly seen. Without now explaining how in practice the rotating field produced by this means is applied to the operation of motors, it may be stated that the production of such motors opened to electrical engineers an enormous field of operations which had hitherto been closed owing to the great difficulty of providing a satisfactory and simple alternating current motor. Until the introduction of the rotating field motor, more commonly called the induction motor, electrical engineers were very largely confined to continuous current motors, there being only an exceedingly small possible range of duties which could be assigned to an alternating current motor. At the same time, where power had to be transmitted over great distances alternating currents were indispensable, and hence many schemes for the transmission of power which had until that time remained undeveloped were put in motion and successfully carried through by means of induction motors. It must not, however, be supposed that two currents having a mutual phase displacement of one quarter of a period are the only kind adopted. It was but a short step from the utilisation of such "two-phase" currents to the introduction and use of three-phase currents, in which three sources of alternating E.M.F. are employed to give three currents having a mutual phase displacement of one-third of a period. The utilisation of two-phase and three-phase currents gives rise to many important problems in distribution and in power measurement, which can only be conveniently stated by the aid of vector diagrams, and with this brief introduction the chief of these problems will now be dealt with in greater detail.

DISTRIBUTION LINES, LINE VOLTAGES, AND LINE CURRENTS.

One of the most important matters affecting the distribution of electrical power is the amount of money that can be profitably sunk in the conductors employed to carry the power from one point to another. Referring again to Mr. J. H. Gordon's machines, it will be perfectly clear that* the power in circuit A would be V × C, and that the same relations are true of circuit B, so that the total power given out by the whole generator if the voltages and currents in the two circuits are identical would be twice V × C. Now if induction motors are to be driven with the arrangements of circuits described, there would be four conductors coming from the power house to the point of utilisation, and for a given total power the current to be carried by each wire must clearly be $\frac{W}{2VC}$, and the total weight of copper involved will be four times that of one conductor of sufficient section to carry the current, C, and of the required length. It was not long after the introduction of two-phase currents before the suggestion was made to combine two of the conductors in one which should form a common return for circuits A and B, and the question at once had to be faced as to what would be the correct section to give to this common return conductor. The question is most easily answered by reference to a simple vector diagram. In Fig. 343 let O A be a crank representing the current in circuit A, and O B the current in circuit B. Since one period is represented by one revolution of the crank, OB must clearly have a displacement of 90 degrees with reference to O A. The actual magnitude of the circuits at any particular instant is, of course, found by projecting the length of the crank in question on to a reference line, such as the line, L L. At the moment depicted in the diagram, therefore, the current in circuit A is 0, while that in circuit B is at its maximum, let us say 100 amperes. The two currents may be compounded by compounding the cranks in the well-known manner to give the resultant O R, and the projection of this upon the line, LL, is at the moment depicted also equal to 100. As the three cranks rotate, therefore, they show by their projections the values of the currents in the outgoing lines or circuits, A and B, and current returning by the common return, R. From this diagram it is clearly seen that the maximum current to be carried by the common return, R, will occur when the crank, R, is vertical in the position now occupied by the crank, B, and that the length of the crank, R, is $\sqrt{2}$ (or 1·414) times as big as either of cranks A or B. Hence the maximum current that has to be carried by the return wire, R, is 1·414 times as great as the maximum current in either A or B; and if the same current density is to be employed its section, therefore, will have to be 1·414 times as great and its weight 1·414 times as great as either A or B. The total weight of copper employed, therefore, by this system of connections is 3·414 times the weight of one conductor carrying the current C, showing a saving of ·586 of that weight over the four separate wires, or, in other words, a saving of about 14½ per cent. The combining, however, of the two wires in one introduces a complication which was entirely absent so long as the two circuits were kept separate. While they were separate the voltage between the lines, A, A′, had nothing whatever to do with the voltage between the lines, B, B′; neither was there necessarily any definite relation between any of these and the potential of the earth. By combining, however, A′ B′ into a common return, R, the outgoing lines, A and B, at once are subject to a definite mutual potential condition, for the combination of the lines, A′ B′, into a common return at once reduces them to one and the same potential, and produces a common datum from which the potential difference of A and B are to be measured.

---

* Assuming $\cos \phi = 1$.

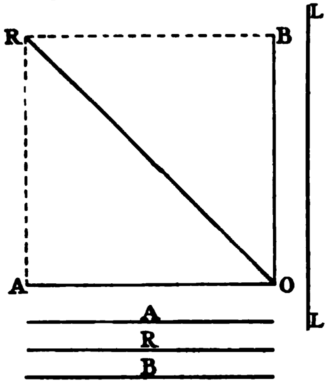


FIG. 343.—DIAGRAM GIVING SUM OF TWO-PHASE CURRENTS IN A COMMON RETURN.

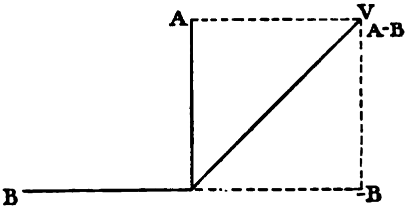


FIG. 344.—DIAGRAM OF VOLTAGE RELATIONS IN TWO-PHASE CIRCUIT WITH COMMON RETURN.

The diagram of the potential difference is identical in appearance to that of the summed currents, and is given in Fig. 344, from which it will be seen that the voltage between the two outgoing wires of a two-phase system with a common return is roughly 40 per cent. higher than the potential difference between any pair where a common return is not employed. In the event, therefore, of one of the outers going to earth the stress on the insulation of the other outer becomes 40 per cent. higher than in the four-wire case; and in order to avoid this additional stress in high potential transmission lines it is customary to earth the common return wire and thus ensure a limit of stress on the insulation of the two outgoing wires.

THREE-PHASE.

Considerations of symmetry readily suggest a transition from two-phase working, such as has just been described, to the employment of three-phase working. The initial difficulty which many people find in grasping the idea of three-phase working may be largely eliminated by keeping constantly in view the precise meaning of the term polyphase. This may be expressed by the statement that in speaking of any number of phases, what is meant is that so many currents are employed, each of which at any instant has its own particular phase (*see* Chapter I., page 360), which is different from that of any of the others at that same instant. If there be a three-phase circuit consisting of circuits A, B, and C, then at some one particular instant—when A, for example, is at its maximum positive—at that same instant neither of the other two will be maximum and positive. As a matter of fact, the other two will both be negative and at half their maximum values, but one will be growing while the other is decreasing, for, with any number of phases, the whole period is always supposed to be equally and symmetrically divided between them. Thus it is seen that each has its own phase at that instant which is different to that of either of the other two. Similarly, if any other instant be taken, three distinct phase properties will be found in evidence at that instant. The precise relationships between the three circuits of a three-phase system are most easily studied from the crank diagram point of view; and in Fig. 345 we have a three-crank diagram relating to circuits A, B, and C, side by side with a curve diagram relating to the same three circuits, the instant of time to which the crank diagram relates being indicated on the curve diagram by the dotted line *t t*. If the three currents whose phases have the mutual relationship indicated be supplied with six wires—namely, a "go" and a "return" apiece—it will be seen that the sum of the currents in the outgoing wires of two of the circuits is precisely equal to the outgoing current in the third circuit. This statement is not complete without defining what is meant by outgoing currents and what is meant by their sum. The wires, A, B, C, if grouped as indicated in Fig. 345, may be regarded as carrying the outgoing currents (A′ B′ C′ being the respective return wires), and the currents in them will have at any one instant the mutual relationships indicated

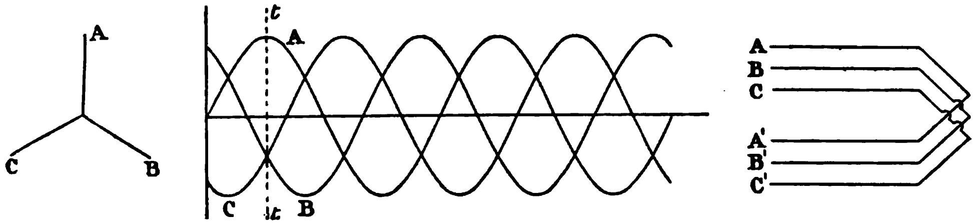


FIG. 345.—DIAGRAM OF THREE-PHASE CURRENT RELATIONS.

on the curve. Therefore, current leaving the supply end may be regarded as positive, and that returning to the supply end as negative. The statement made just above now amounts to this, that if at the instant *t* the current in A be 100 amperes positive, there will be in B and C conjointly 100 amperes negative. At the instant in question the currents in B and C are equal, and will therefore be 50 amperes each. Now with the connections indicated, the out-going current of 100 amperes in A is brought back by its own return wire, A′; but this is clearly an unnecessary expenditure of copper, since, by joining the distant ends of A, B and C together at that particular instant, B and C will serve to convey the return current, leaving the station by A: nor is this true only of the instant referred to, but is true at every instant of the complete cycle. This is most readily expressed —and those who have an elementary knowledge of trigonometry will grasp it at once— by saying that $\sin \theta^{0} + \sin (\theta^{0} + 120^{0}) + \sin (\theta^{0} + 240^{0}) = 0$. Another way of expressing it electrically is by saying there is no tendency to cause any accumulation of electricity at the point of junction of A, B and C at any instant, and hence they may be joined together without giving rise to unnecessary forces in order that Kirchoff's law may not be broken. Of course, what has been said of circuit A applies to circuits B and C, since the case is perfectly symmetrical, and all the three return wires, A′, B′, C′, are dispensed with, and the three-phase currents are supplied through the three outgoing wires only, A, B, C. This, of course, means a very considerable saving in cable, and if we consider the power to be transmitted we find that with the six wires, A A′, etc., if the voltage between any pair is V and the current carried by any one is C, the total power is three times V C, and the total weight of copper required is six times that of a single wire to carry the return current. When, however, the three return wires are eliminated, the power transmitted is the same, although the weight of cable is reduced to one-half—namely, three times that of any one wire. While this is so, however, the joining together of the three cables creates a common datum point for potential, as in the two-phase case with three wires, and this now imposes a mutual potential relationship between the wires which did not necessarily hold good before they were joined. If the arrangement of connections be that indicated in Fig. 346, where L, L, L, indicate groups of lamps each requiring the same current, the voltage relationship between the lines is given by the crank diagram, Fig. 347. Here what is wanted, for example, is the potential difference between A and C, that is, A′ C. We, therefore, draw a crank to represent C, as indicated in dotted lines, and complete the parallelogram by which it is compounded with the crank, A, thus obtaining the crank, V, giving the resultant potential difference between A and C. The length of this is readily seen by elementary trigonometry to be $\sqrt{3}$, or 1·731 times as long as either of the cranks A, B or C, and, of course, the relationship between any other pair, such as A B or B C, is precisely the same. The internal connections in the generator are more fully described in the following section of this book, but for the present it must be pointed out that they correspond precisely with those of the load indicated in Fig. 347—that is to say, if in Fig. 348

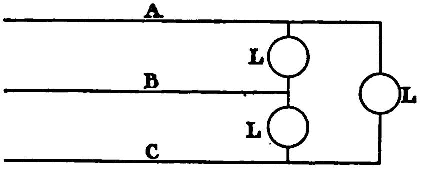


FIG. 346.—THREE-PHASE LOAD CONNECTIONS.

three-phase currents were supplied by three generators whose windings are shown at *a*, *b*, *c*, each generator supplying one phase, these three generators might all be connected together so as to eliminate the return wires, A′, B′, C′, by connecting the corresponding ends to one common point of junction, J. In point of fact, three separate machines are never used — at best they might be used with three spindles rigidly connected together in order that their phase relationships should remain unchanged—but it is, of course, far simpler and preferable from every point of view to arrange the three windings upon one machine, thus obtaining economy of space and constancy of phase relationship at once.

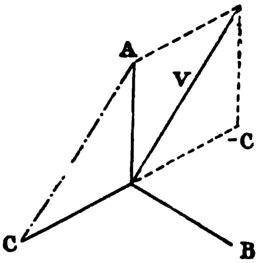


FIG. 347.—THREE-PHASE (THREE WIRES) VOLTAGE RELATIONS.

If the three windings on the one machine are thus connected together, so as to have one common junction point and three free ends as shown in Fig. 348, the three windings are then commonly referred to as the three phases of the machine, *a*, *b*, *c*, and the machine is said to be star connected.

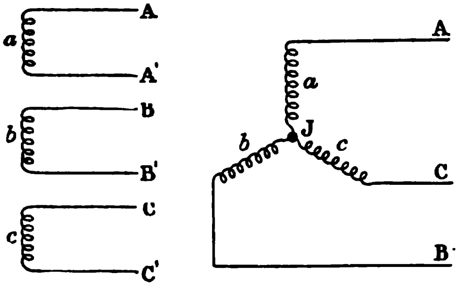


FIG. 348.—STAR-CONNECTED GENERATOR CIRCUITS.

It may be noted that the diagram, Fig. 348, shows the windings so drawn as to indicate after the manner of a crank diagram the phase relationship as well as the star connection. It is, however, possible, to arrange the windings differently. The three imaginary separate machines might, for example, have been arranged so that the wires A′ and B, B′ and C, and C′ and A were amalgamated, thus providing three wires instead of six. In this case the relationships of voltage and current are different from those in the last. This method of connection is given in Fig. 349 and is known as the delta or mesh connection, from the appearance of the crank diagram; and, since the wires now carry the sum of the currents in two phases, the total current in any one wire will be $\sqrt{3}$ the current in any one winding, while the voltage between any pair of wires will be merely the voltage of one phase, *a*, *b* or *c*. The two methods of connection, star and mesh, may thus be regarded as series and parallel connection respectively, since in the former case the voltages are summed, while the current in one line is merely that of one phase, and in the delta case the currents are summed and the voltages between the lines are merely the voltages of the phases.

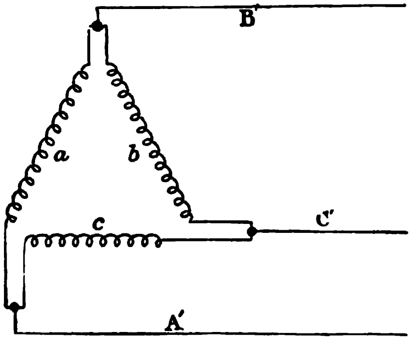


FIG. 349.—MESH-CONNECTED GENERATOR CIRCUITS.

The production of a rotating field by means of three coils wound on a ring in place of the two seen in Fig. 340, may be easily elucidated by the reader for himself by means of a series of step-by-step diagrams on the same basis as that given in Fig. 342.

MEASUREMENT OF POWER IN POLYPHASE CIRCUITS.

General theorems relating to the measurements of complex circuits have already been given on page 290, Section V., but the methods employed in practice are given here. If the load in all phases is the same, both in magnitude and ϕ, then clearly for a two-phase circuit the total is twice, and in a three-phase circuit three times, the power in one phase. Where the load is known to be of this perfectly symmetrical character, as when it consists entirely of induction motors, the power in one phase only need be measured, and the result multiplied by two or by three, as the case may be.

If, however, connections are made to one phase only of a two-phase system for lamps or other work, in addition to a motor load, or if the extra load is not equally divided between the two phases, both for inductive effect and magnitude, the case is not symmetrical or "balanced," and the power must be measured in each phase. The four-wire case needs no further remark. The common return case of Fig. 343 is dealt with by using two wattmeters with one main coil in A and one in B, and the shunt coils connected to the common return by one terminal, and by the other to their respective main coils. The sum of the two readings gives the total power. If the load is balanced the two readings are identical, of course, and one instrument might be dispensed with.

In a three-phase circuit the neutral point is not accessible, as a rule, outside the central station. In such a case an artificial neutral point (*i.e.* one of exactly the same potential as the neutral point if the system is balanced) may be found by joining three equal, non-inductive resistances together, star fashion, as shown in Fig. 350, by the letter N and resistances, C. Three times the reading is then the total power, whether the generator is either star or mesh wound. Where the neutral point of a star-wound machine is accessible, connection is made direct thereto, so avoiding the extra resistances, C. Where neither the neutral point is available, nor are suitable resistances at hand, connection may be made as in Fig. 351, the free end of the shunt circuit being placed first on phase 1 and then on phase 3. The sum of the readings gives the total power. This is shown to be true by Fig. 352, from which it is clear that the two readings are V_{2-1} C_2 cos ($\phi + 30°$) and V_{2-3} C_2 cos ($\phi - 30°$) respectively. By expanding cos ($\phi + 30°$) and cos ($\phi - 30°$), and adding the expressions for the two readings, they are seen to be

$$2 \text{ V C} \cos \phi \cos 30°,$$

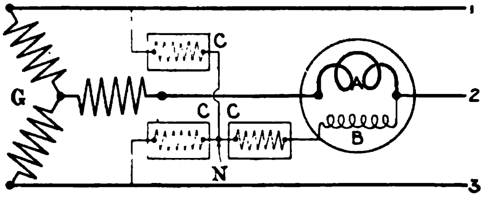


FIG. 350.—ONE WATTMETER MEASURING THREE-PHASE POWER; BALANCED CIRCUIT.

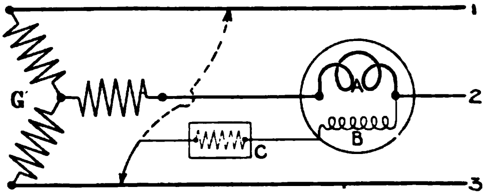


FIG. 351.—ONE WATTMETER MEASURING THREE-PHASE POWER; BALANCED CIRCUIT; NEUTRAL POINT INACCESSIBLE.

since V_{2-1} and V_{2-3} are the same, and may be written V. But V measured as shown is $\sqrt{3}\,v$ if v is the voltage in one phase; further, cos 30° is $\frac{\sqrt{3}}{2}$, and, by substituting, we get the sum of the readings as

$$3\,v\,\mathrm{C}\cos\phi,$$

which is clearly correct. In a mesh-wound circuit the only difference is that C is $\sqrt{3}\,c$, where c is the phase current. (*See* pages 399 and 401.)

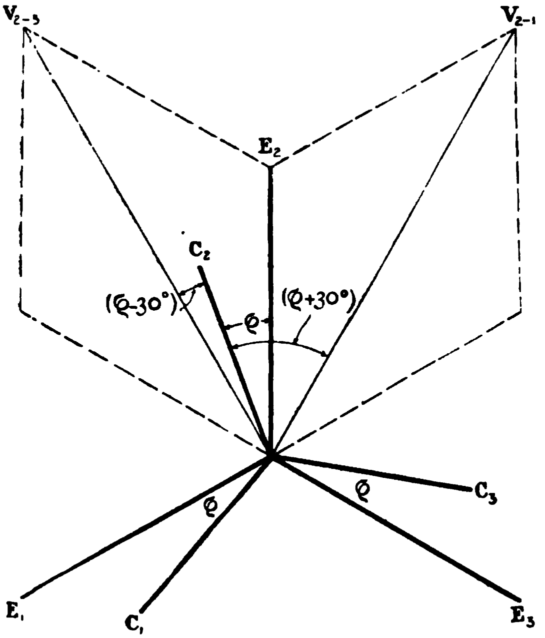


FIG. 352.—VECTOR DIAGRAM ILLUSTRATING METHOD OF FIG. 351.

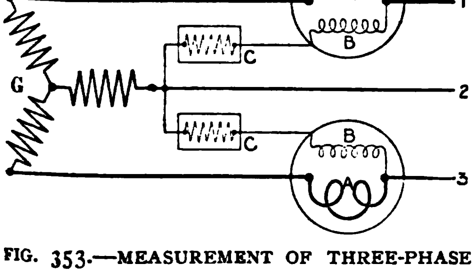


FIG. 353.—MEASUREMENT OF THREE-PHASE POWER; UNBALANCED CIRCUIT.

If the circuit is unbalanced, the measurement of total power is made by using two wattmeters connected, as shown in Fig. 353. It is essential that the connections be carefully made since, in a very badly balanced system, the reading on one instrument may have to be negative. In order that the readings may both have the proper sign, the shunt circuits of the instruments must be so connected as to give positive readings when current is flowing from *right to left* (as seen in the diagram) through each coil, A, and *out* from the middle phase 2 through each shunt coil B to the outer wires 1 and 3.

In Figs. 350, 351, and 353 the generator is indicated by three circuits, star-connected. It is, of course, immaterial whether the circuits be those of a motor or of a generator. Neither will the measurements be affected by giving the machines a mesh-winding instead of a star, since the power transmitted by the three mains obviously depends upon the currents and voltages and their phase relations, but upon nothing else. If, therefore, the measurements take full account of these quantities and relations, it is clear that the connections of the circuits must be immaterial. In general, the most readily applicable method is that shown in Fig. 351, and it is sufficient, provided the circuit may be fairly assumed to be balanced. Where, however, nothing is known definitely as to whether it be balanced or not, two wattmeters should be used as in Fig. 353. In the factory the neutral point of a motor or star-wound generator is usually accessible, and the best method is to take measurements on one phase only, or, if the balance of a generator load be not above suspicion, in all three phases.

CHAPTER V.—ALTERNATING CURRENT TRANSFORMERS.

TYPES—TRANSFORMER DIAGRAMS—HYSTERESIS AND EDDY CURRENTS—LEAKAGE—OUTLINE OF DESIGN.

TYPES OF TRANSFORMERS.

Alternating currents have the great advantage of being capable of transformation from one voltage to another without the use of rotating machinery. Suppose a coil of wire connected to a source of alternating current supply be placed near a second coil, the ends of which are connected to an electrostatic voltmeter, as shown in Fig. 354, the alternating current in A sets up an alternating flux which rises and falls between positive and negative maxima in the same way as the current. If the coil, B, be brought sufficiently close to A, some of the flux from A will thread through B, and so induce an E.M.F. in it, which will be indicated upon the electrostatic voltmeter, V. Of course, some of the flux from A will not cut B at all, but will " leak " back through the space, C, between the coils, the amount so doing depending on the magnitude of the space, C. The closer the coils are brought together, the less proportion will the leakage flux bear to the total flux, and the farther apart they are the greater will be the proportion, until if B is placed sufficiently far away from A, practically all the flux leaks, and there is no voltage at all induced in B. Any flux is a leakage flux which does not cut or thread *both* windings. Suppose now that we attempted to take a current from B. The leakage would be very much increased, as the ampere turns on B would oppose the effort of those on A (*see* page 9). The effect of increasing the difficulty of passage through B would be to divert still more of the flux through the gap, C. In order to increase the amount of flux passing, an iron bar might be inserted through both coils. This would vastly improve matters by increasing the *total* amount of flux, owing to the reduced reluctance of the magnetic path, while the actual magnitude of the *leakage* flux would remain about the same, making it a very much smaller percentage of the total flux. Although, by the introduction of an iron core into the coils, we have greatly improved matters, we have not yet reached the best form obtainable. The return path for the flux is still through air, and if in addition we provide a return path of iron, the total flux will be again increased, and although the leakage will also probably be somewhat greater, this can be reduced

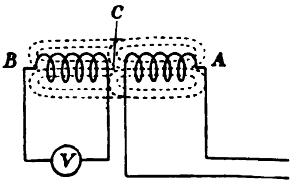
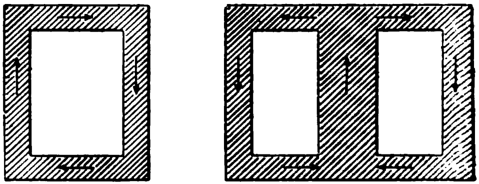


FIG. 354.—ELEMENTARY CORELESS TRANSFORMER.



"Core" type. "Shell" or "Mantle" type

FIG. 355.—TYPES OF TRANSFORMERS.

by other means. As before noticed, the distance between the coils has a very large effect upon the leakage, and it is essential that the coils should be placed as near together as possible. It is good practice to split the primary and secondary windings up into sections, and sandwich them between one another, suitable insulation being placed between them; sometimes, especially for high-tension work, the primary and secondary are wound on concentric insulating barrels, the windings being as close to one another as is consistent with safety. The iron return path can be provided in two ways: either the path can be completed on one side only, or it can be completed on both sides. The first type is known as a "core"-type transformer, and the second as a "shell" or "mantle" type. The iron structures of both kinds are shown in Fig. 355, in which the arrows indicate the path of the main flux.

In the "core" type, bobbins containing the windings are placed upon both limbs of the core, half the primary and half the secondary being on each limb. In the "shell" or "mantle" type, however, the whole of the windings, both primary and secondary, are placed upon the centre limb, the outside limbs merely forming return paths for the flux. The derivations of the terms "core" and "mantle" or "shell" are at once obvious from the shape of the iron circuits, as in the first case the iron only forms the "core" of the winding, and in the second it also forms a "mantle" or "shell" partly covering the windings. The chief advantages of the "core" type of transformer are the accessibility of the windings, and the smallness of the objectionable magnetic leakage fluxes. Also, the windings are divided upon two limbs, each capable of carrying the total flux, enabling a less length of mean turn for the winding to be used than is possible on the "shell" type, where all the windings are placed on one limb of the same section as in the core type. In the "shell" type the magnetic leakage is also considerably greater than is the case with the "core" type, and with few exceptions, the core type is adopted as the standard at the present day.

TRANSFORMER DIAGRAMS.

One of the most useful applications of the vector diagram method of working is found in the solution of transformer problems. At first sight the transformer question seems to be a very difficult one to approach; on account of the large number of variable quantities concerned, apparently the only constant quantity being the applied E.M.F. However, if the problem be approached by way of the flux, which is common to both primary and secondary windings, the main difficulties in the way are overcome.

We assume for the present that the field is exactly in step with the current that produces it, and from what has already been said concerning self-induction it is clear that there will be an E.M.F. of self-induction lagging 90 degrees behind both current and magnetism. If we make our coil of fairly stout wire we make the voltage represented by C R insignificant in comparison with the back E.M.F. of self-induction. In this case the E.M.F. to be supplied to the terminals of the coil must clearly comprise two components, one equal and opposite to the back E.M.F. of self-induction, so neutralising the latter, and the other keeping step with the current and providing what is needed as stated by Ohm's law to overcome resistance. This latter we have assumed negligible by comparison with the former, and under these conditions we have the total applied E.M.F. acting 180 degrees in advance of the E.M.F. induced by self-induction. Now if we consider the E.M.F. induced in the second coil referred to, the alternations of magnetic flux through that coil are clearly identical with those through the first coil, and will set up in the second an E.M.F. similar in all respects but magnitude to the E.M.F. of self-induction in the first. As regards magnitude, however, the only necessary relation between the E.M.F. of self-induction in the first coil and the induced E.M.F. in the second is that the amount of each per turn of coil is the same. If, for the moment, we neglect the leakage the alternating flux is the same, and the rate of change of flux through each turn in each coil is the same at every instant. The second coil, hence, is the seat of alternating E.M.F., so directed that if the ends be joined and the current be allowed to flow, the current would oppose the change of magnetic flux at every instant. It is clear, therefore, that if we wind a coil of 100 turns on one side of the ring, and one of 500 on the other side, and apply an E.M.F. of 200 volts to the first, that there will be generated in the second an E.M.F. of 1,000 volts. If, on the other hand, the second coil had contained 75 turns only the E.M.F. generated in it would have been only 150 volts.

By applying this principle, therefore, we can devise apparatus which, if supplied with power in one way, say at a low voltage, is capable of returning that power from a second coil at a different voltage, either a higher or a lower, according to the proportion which the number of windings in the secondary coil bear to that in the primary. As a matter of fact, however, our elementary transformer as outlined above would be quite useless for practical work. The first and chief objection to it lies in the fact that it has presumably a solid iron core. This solid iron core would become the seat of very heavy eddy currents which would be quite capable in themselves of absorbing a very large amount of power, and hence, greatly discounting the power which would be transferred from the primary to the secondary coil. We must clearly, therefore, construct some kind of iron link between the two coils which shall be free from the objectionable eddy currents. An iron link is a necessary part of the transformer, since it performs the function in the case we have given of directing the flux generated by the primary coil through the convolutions of the secondary and so reducing leakage. This, however, is not the only function of the iron core, for we may clearly wind the secondary outside the primary, in which case the flux generated by the primary coil would be forced to traverse the secondary, at any rate, without the loss of more than a small fraction of the flux. In the absence of an iron path for the magnetic lines, however, we should find that the coefficient of self-induction of the primary coil was very much less than with it, and hence on switching on our E.M.F. to the terminals of the primary coil there would be a flow of wastefully large currents, whose energy would be dissipated in the heating of the copper. The presence of iron, however, with its permeability so greatly in excess of that of air, results in a higher coefficient of self-induction, and hence in a correspondingly decreased current through the primary. In order to provide this necessary iron link and yet to avoid the production of eddy currents in it, we may construct the iron path for the magnetism either of iron wire or of iron stampings. If the core is of ring shape we may construct it of iron wire coiled into a ring as iron wire is commonly sold, then the path of the eddy currents will be one of much higher resistance than in the case of solid iron. Let us consider what the general direction of eddy currents necessarily is.

Eddy currents must of necessity circulate in paths whose plane (or part of which can be projected on to a plane) is at right angles to the magnetic field, and hence if we split up the iron in any way at right angles to the path of the eddy currents, we shall succeed in reducing them. By building up the ring of iron wire we break up the section of the iron so that it consists of a great number of contiguous areas instead of one solid mass. If we, on the other hand, build up the iron ring by assembling a number of iron discs together, each of these discs should clearly be of the same inside and outside diameters as those which the finished ring is intended to have, and we shall reduce the eddy currents to flowing in a path whose area is rectangular, the long sides of the rectangle being the radial width of the discs and the short sides being their thickness. The resistance in the path of the eddy currents will therefore depend upon the thinness of the discs. It will be as well at this stage to compare the way in which the sub-dividing of the iron ring by wires or discs respectively affects the magnitude of the eddy currents. Consider any circular area of one inch diameter in the original solid iron ring. This may be replaced by 91 wires, each one-eleventh of an inch in diameter, arranged in ten layers around a central wire; we shall only get altogether 0·752 as much iron into the inch circle as we had before, the rest, of course, being occupied by the air which will fill the interspaces between adjacent wires. The eddy currents will now be confined to travelling round and round in the circular paths seen in the section of a wire, and if we compare the flux in one of these wires with that in the solid circle we find that the relative value is 1-91th and hence the total E.M.F. generated is 1-91th. The resistance may be estimated as follows: Consider the path of two eddy currents in a solid cylinder when the magnetic flux is in a direction parallel to the cylinder axis. The eddy currents will flow in circular paths concentric with the cylinder. The mean length of the paths is $\frac{1}{2}\pi r$ (*see* Fig. 356), while the cross-sectional area of the path is that of the plane indicated by dotted lines, and is clearly $r \times l$; the resistance is therefore proportional to

$$\frac{\frac{1}{2}\pi r}{r \times l} \text{ or } \frac{\pi}{2l},$$

and is independent of the value of r, and is the same for any two wires of the same length, l, but of different diameters. On the other hand, however, the E.M.F. in the two sizes of wire under consideration is proportional to the flux carried by each, and in the smaller one is 1-91th of that in the larger. The eddy current strength will be reduced in inverse proportion to the number of wires employed in the equivalent circle.

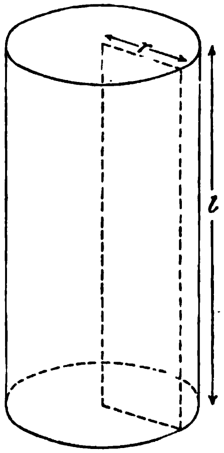


FIG. 356.—RESISTANCE OF EDDY CURRENT PATH IN A CYLINDER.

Next consider the case of discs or plates. If we halve the thickness of the discs employed we halve the area for the flux capable of generating any eddy current and the E.M.F. is therefore halved. The mean length of path may be slightly reduced, but that may be neglected, while the area it has to traverse is reduced again by one half, so that in this case the value of the currents will be in inverse proportion to the square of the thickness of plate employed. The use of plates has, moreover, the advantage over that of wires in that it does not involve so much waste space, since the plates lie flat up against each other and need only be separated by a piece of tissue paper or the thickness of a light coat of varnish in order to keep them insulated from one another against the eddy currents. Indeed, so small is the E.M.F. driving eddy currents that some makers are content to rely upon the resistance interposed between adjacent plates or laminæ by the film of oxide which gives thin sheet iron its beautiful blue and brown colouring. The cores that are built up of iron wire are generally insulated against eddy currents by drawing the wire through a bath of very thin shellac varnish, which may be further diluted by the admixture of resin, which is, of course, much cheaper than shellac.

Unfortunately we do not get over all the difficulties by merely making the iron ring of wires or other laminations, although this may suffice to reduce eddy currents to an altogether inappreciable amount. Let us consider exactly what will go on in such a transformer when we put it to actual work. The core shall be built up of discs of iron forming a ring, over a portion of which we wind our primary coil, and over a portion diametrically opposite this we wind our secondary. Let us first assume that we put an equal number of turns in each coil and leave the ends of the secondary disconnected from anything. On applying the alternating E.M.F. to the ends of the primary coil a small current flows, which, by reason of the self-induction of the coil lags practically 90 degrees behind the applied E.M.F. The question at once arises, how big is this ? and the answer is that it is only just so great as will provide the ampere-turns needed to magnetise the core. But to magnetise the core how much ? Just so much that in threading, or rather, in oscillating through the turns of the primary, the flux shall be sufficiently high to generate a back E.M.F. very nearly equal to that which we apply to the terminals. If this back E.M.F. is very nearly equal to the applied E.M.F. there will only be left a small margin just sufficient to drive the magnetising current through the primary coils, and as these should contain a large number of turns the current cannot rise to an undue or wastefully large value. In fact, in practice the magnetising current is so small, and the resistance of the winding so small compared with its self-induction, that the difference between the applied E.M.F. and the back E.M.F. of self-induction is too small to be appreciable (at no load). Now, as we have already seen, the alternating flux sets up such an E.M.F. in the secondary coil as will, if it can, produce a current in the latter opposing the flux. Let us connect the two ends of the secondary coil together through a fairly high resistance, such as may be readily formed of incandescent lamps. The result of this is that the secondary coil will now be carrying a current which at every instant opposes the magnetic flux through it, and if we consider the ring as a whole it is now provided by the primary with magnetising ampere turns and by the secondary with demagnetising ampere turns. The tendency of this is, of course, to lessen the total flux in the iron ring, and if this flux does diminish, the back E.M.F. of the primary coil will also diminish, and the applied E.M.F. which we assume to be constant will therefore be able to send a larger current through the primary. In point of fact this is what happens, namely, that so soon as current is taken out of the secondary coil the demagnetising effect due to the secondary current is compensated for by an increased magnetising effect due to the primary, which draws a larger current from the mains, rising indeed to such a value that the excess of ampere turns in the primary over the ampere turns in the secondary is, roughly speaking, sufficient to restore the magnetic flux to the original no-load value which we first considered. A complication, however, enters the question at this stage which cannot be satisfactorily handled except by reference to what are known as clock diagrams.

One of the causes of complication is the difference in phase of the primary and secondary currents, and another is the necessity of supplying power to the transformer which does not get transferred from the primary to the secondary, but is absorbed by the transformer in hysteresis and eddy currents, mainly, of course, in the former. The waste of power further due to the heating of the primary and secondary coils is a minor complication less troublesome to discuss. The hysteresis loss is of a nature which has already been explained in Section IV., page 201, and in a transformer where the iron is usually carried through anything from 25 to 100 cycles per second, the loss may amount to something quite considerable. The total energy demanded is, of course, proportional to the total mass of iron, and it is hence customary to speak of the ergs per cubic centimetre per cycle, of the watts per pound at 100 cycles per second, or of the watts per cubic inch at 100 cycles per second. This loss goes on in the transformer iron at all loads, and since the flux density is fairly constant from no-load to full-load, the hysteresis and eddy current loss may be regarded as approximately constant at all loads.

Let us now proceed to apply what are above referred to as clock diagrams to considerations of what goes on in an alternating current transformer. On page 355 alternating quantities were compared in their behaviour to the behaviour of a piston driven from a rotating crank, and a method was referred to there by which a curve of sines could readily be constructed by reference to a rotating crank. In order to simplify the methodical discussion of the subject, it is usual to assume that the alternating quantities with which we deal do follow a sine law with reference to time.

Since the alternating quantities present in a transformer all oscillate with the same frequency, we may clearly represent them by a number of cranks whose lengths correspond to the representative quantities which they represent, all mounted upon one spindle and rotating at one speed. This speed must be such that a crank revolves in the time taken by a quantity to effect one complete alternation. Now let us apply this principle to our transformer, and be it noted we shall arrive most easily at a solution of the problem if we attack it by way of the magnetic field first. It is quite clear that if the transformer is in operation at all it operates by virtue of an alternating magnetic field which threads both primary and secondary coils.

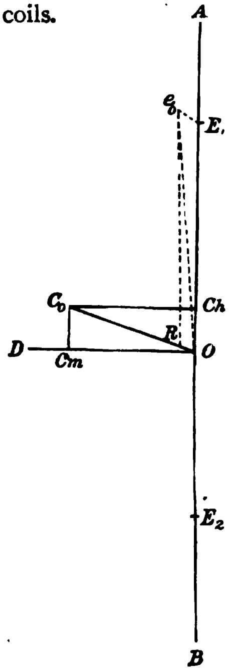


FIG. 357. — TRANSFORMER DIAGRAM ; OPEN SECONDARY CIRCUIT.

Let us consider, in the first place, a one-to-one transformer and suppose that, in Fig. 357, *OD* represents in phase the flux which is common to both primary and secondary windings. Then along *OB* we can set out OE_2 equal to the E.M.F. of self-induction in the primary circuit, and, therefore we can set out, at 180° along *OA*, a distance $OE_1 = OE_2$ as the E.M.F. which we have to apply to the primary to overcome the E.M.F. of self-induction. The flux, *OD*, must, of necessity, be associated with a current producing it, and this we may set off as OC_m in phase with OD, called the "magnetising current."

Now if the iron of the transformer were perfect, and occasioned no loss, and if the no-load current produced no loss in traversing the primary winding, we could represent the true no-load current by OC_m. Of course, this would mean that no power was being supplied to the transformer, and as is well known, energy *is* dissipated even on no load (by both iron and copper losses). It is usual to account for power involved in the iron losses by the simple statement that they heat the iron, and must therefore be represented by some portion of the power supplied to the transformer. It is, however, preferable to consider the elements that operate to occasion the losses, and the way they operate. There are two distinct sets of causes—hysteresis and eddy currents. The expenditure of energy in the reversal of magnetisation has been explained on page 202, and may be further realised, in the case of an alternating current, by considering the fact that the current must reverse and reach a definite value in the reversed direction *before* the magnetism reverses. The magnetism vector, therefore, must lag behind the current vector, and since the E.M.F. is (apart from copper loss) 90° ahead of the magnetism, it must be less than 90° ahead of the current. This means that cos ϕ has a finite value instead of being zero, as it would be if the current and magnetism were exactly in step with each other. The eddy currents tend to make the current lead still further in advance of the magnetism. The E.M.F. producing the eddy currents is necessarily identical in phase with the E.M.F. of self-induction, since they are both produced by the same changes of flux. The eddy currents therefore are driven by an E.M.F. 90° behind the magnetism, and probably lag somewhat behind that E.M.F. But wherever they circulate they tend to oppose the changes of magnetism, and we may very fairly represent their action by that of a short-circuited turn of wire embracing the iron. If we assume perfect lamination and no eddy currents, but leave this short-circuited turn (one closed ring) of wire embracing the iron, we can simulate the effects of the eddies exactly; the magnitude is easily adjusted by considering the turn to be made of appropriate resistance. The ring, however, presents the idea of magnetomotive force more simply since the *ampere turns* it occasions are more easily grasped than those of the eddy currents which circulate in undetermined paths. The joint effect of the hysteresis and eddy currents is shown in the diagram (Fig. 358), where it is seen that the result is to necessitate a larger exciting current than would otherwise be needed, and one more nearly in phase with the applied E.M.F. The eddy current ampere-turn vector CS_e, in the third diagram, is resolved into two components (shown dotted), so that one is 180° behind the flux, and represents demagnetising effect, while the other involves power in conjunction with the applied E.M.F. We have so far used the vectors for ampere turns, but we may equally well use them as current vectors, since the turns have no vector properties, but are merely numerals. The change is merely one of scale, so that whereas 1 centimetre may have represented 100 ampere turns, it also represents 5 amperes if the coil has 20 turns.

Returning to the transformer diagram (Fig. 357), we now see that if OD is the flux vector, the true no-load current vector will be as indicated at C_o (compare CS_o in Fig. 358), and this vector is usually considered as made up of two components, C_h (corresponding to CS_w in Fig. 358) and C_m, which corresponds to the sum of CS_μ and the eddy demagnetising effect.

In applying a diagram to a given transformer we know the weight of iron, and can calculate the hysteresis and eddy losses (the copper losses at no load are negligible by comparison); we therefore set off OC_h to represent a current component, which, in conjunction with the E.M.F., will indicate the power required to supply these losses, and by compounding OC_h with OC_m, we get OC_o, which is the true no-load current of the transformer. As the flux, OD, cuts both primary and secondary windings, we can represent along OB the E.M.F. induced in the secondary winding. Since the transformer has a one-to-one winding, that is, the primary and secondary windings have the same number of turns, we can represent the secondary E.M.F. by OE_2, which also represents the primary E.M.F. of self-induction. If the windings have not the same number of turns, it is still the simpler way to draw the diagram for a one-to-one case, and correct by multiplying by a factor, or, what is the same thing, by using different scales for the secondary quantities.

To obtain the E.M.F. which must be applied to the terminals of the primary, we must compound with the OE_1 a small E.M.F., OR, for the voltage drop in the primary, equal to the no-load current multiplied by the primary resistance. The resultant Oe_o is the E.M.F. which must be applied to the primary to give the E.M.F. OE_2, of the secondary.

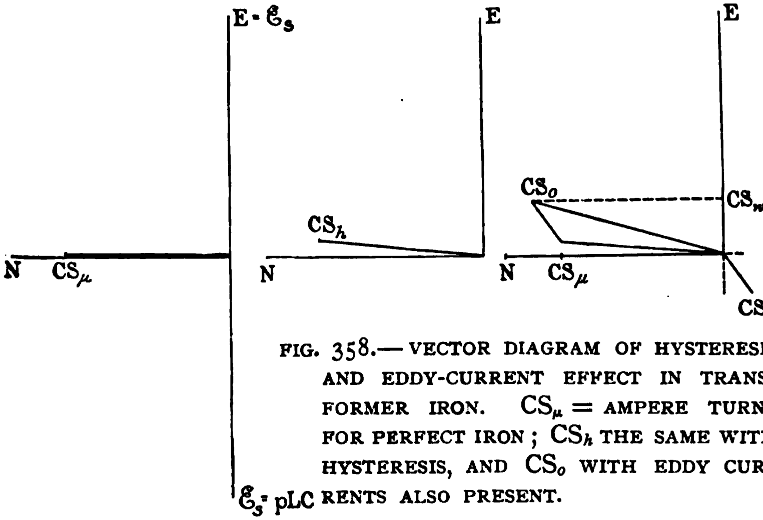


FIG. 358.—VECTOR DIAGRAM OF HYSTERESIS AND EDDY-CURRENT EFFECT IN TRANSFORMER IRON. CS_μ = AMPERE TURNS FOR PERFECT IRON; CS_h THE SAME WITH HYSTERESIS, AND CS_o WITH EDDY CURRENTS ALSO PRESENT.

Suppose now that a non-inductive load be thrown upon the secondary circuit, and that the magnitude of the secondary current be represented by OC_2 in Fig. 359, the line oc_1, therefore, represents the current necessary in the primary to balance this. The no-load current OC_o is still required to magnetise the iron and supply the losses, and the total primary current is obtained by compounding OC_o and OC_1, giving the resultant OC. It is noticeable that, although the secondary current is in phase with its E.M.F., the primary current lags behind its E.M.F., due to the effect of the magnetising current.

The terminal E.M.F. of the secondary is represented by OE_2, which, to give the internal secondary E.M.F., must be increased by a small amount E_2e_2, equal to the voltage drop due to the resistance of the secondary winding, and in phase with OC_2. The primary internal E.M.F. required to balance OE_2 is represented by OE_1, equal to it in magnitude and opposite in phase. Again, to get the primary terminal E.M.F. Oe_1, we must compound with OE_1 a small amount OR, in phase with the primary current, and equal to the voltage drop due to the primary resistance. The resultant Oe_1 represents in magnitude and phase the applied primary E.M.F., requisite to give a secondary terminal E.M.F. of OE_2.

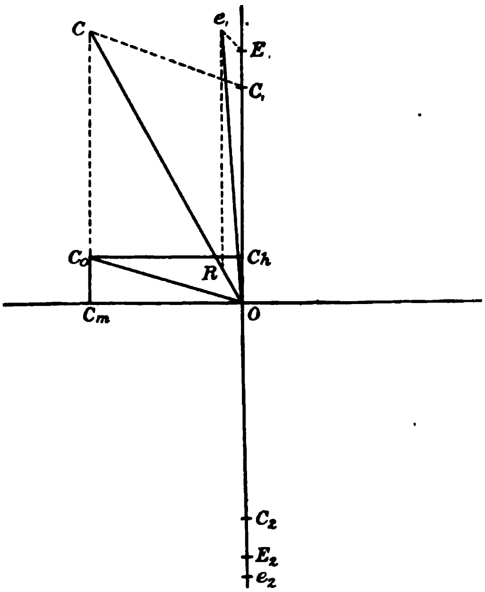


FIG. 359.—DIAGRAM OF LOADED TRANSFORMER; NON-INDUCTIVE LOAD; NO LEAKAGE.

If now, instead of a non-inductive load, an inductive one is thrown on the secondary, the condition of affairs is shown in Fig. 360, OC_2 is the inductive secondary current, to balance which the current OE_1 is required in the primary. Compounding this, as before, with the secondary current, the resultant primary current, OC, is obtained.

If OE_2 be the secondary terminal E.M.F. required on load, then to find the internal secondary E.M.F. necessary to give this, we must compound a voltage OR_2, equal to the secondary voltage drop due to resistance, and in phase with the current OC_2 with the terminal E.M.F. Oe_2. The resultant, Oe_2 gives the internal secondary E.M.F. To account for this, we must have an equal E.M.F., OE_1, but opposite in phase, in the primary. In addition to this we have to take into consideration the primary voltage drop. This is done by compounding with OE_1 the voltage drop OR_1, in phase with the primary current, and getting the resultant Oe_1, the primary terminal E.M.F. required. It will of course, be noticed that in the case of the primary, the terminal E.M.F. is greater than the internal E.M.F., while in the secondary the internal E.M.F. is greater than the terminal.

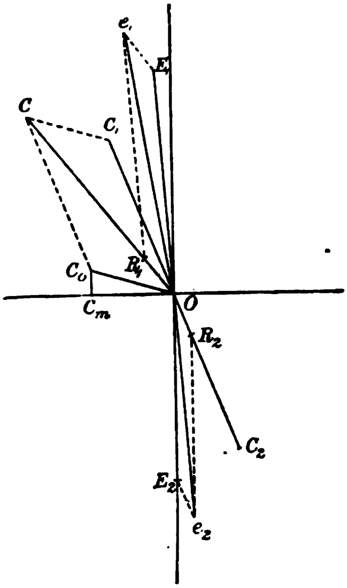


FIG. 360.—TRANSFORMER DIAGRAM WITH LAGGING SECONDARY CURRENT; NO LEAKAGE.

Fig. 361, shows the same diagram drawn for a capacity load on the secondary, the secondary current OC_2 leading on the secondary E.M.F. The lettering is exactly the same as for the previous diagram, and the cycle of operations is identical.

All the foregoing diagrams are based upon the supposition that exactly the same flux cuts both primary and secondary windings. As a matter of fact, this is *not* the case, there being a leakage flux from the primary which does not cut the secondary, and one from the secondary which does not cut the primary. Professor Kapp's method of looking at the problem makes this rather clearer. He says a transformer possessing leakage may be represented by a perfect transformer (*i.e.* one with no leakage) in series, with both the primary and secondary of which are connected choking coils, as shown in Fig. 362.

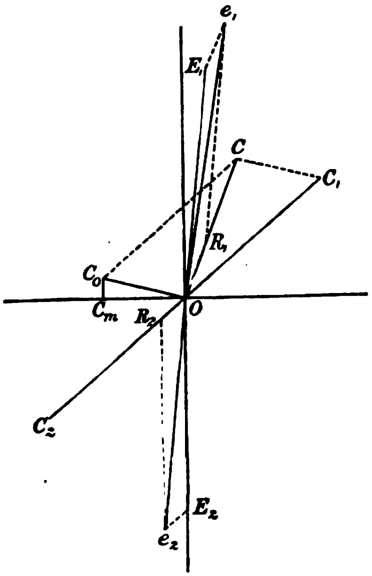


FIG. 361.—TRANSFORMER DIAGRAM WITH LEADING SECONDARY CURRENT; NO LEAKAGE.

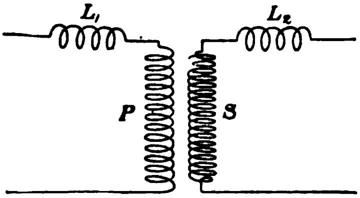


FIG. 362.—REPRESENTATION OF MAGNETIC LEAKAGE EFFECT IN TRANSFORMER.

It can thus be taken that there is one main flux, N, common to both primary and secondary windings, and two leakage fluxes, N_1 and N_2, which cut only the primary and secondary windings respectively, these being the fluxes in the choking coils, L_1 and L_2. We can now proceed to the construction of the diagram for the transformer, taking leakage into account.

Suppose, in Fig. 363, OE_2 to be the secondary terminal E.M.F., and OC_2 to be the secondary current lagging behind it. Now it is the secondary current, OC_2, which produces the leakage flux, N_2, that does not cut the primary winding. This flux, N_2, is in phase with the current producing it, and, since it cuts the secondary winding, produces an E.M.F. in it at right angles in phase to OC_2. Let us call this E.M.F. Oe_2. The voltage drop due to the resistance of the secondary winding takes place as seen before, and is marked at OR_2. Thus, the internal voltage generated by the secondary has to provide OE_2 terminal volts, and to overcome Oe_2 and OR_2. We therefore compound together OE_2, OR_2, and Oe_2, as shown, giving as resultant $O\mathcal{E}_2$, the internal secondary voltage. This voltage is produced by the main flux, N, cutting the secondary winding, and this flux can therefore be represented in phase by the line OD at right angles to $O\mathcal{E}_2$.

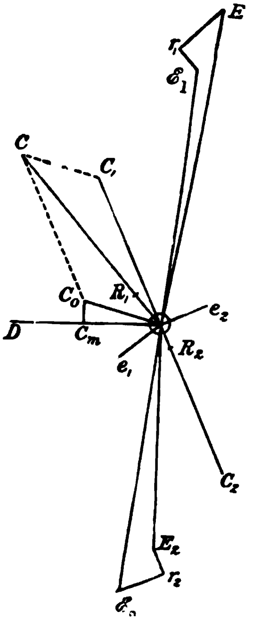


FIG. 363.—TRANSFORMER DIAGRAM TAKING LEAKAGE INTO ACCOUNT; LAGGING SECONDARY CURRENT.

The flux N, as we have seen, is common to both primary and secondary windings, and therefore also induces in the primary winding an E.M.F., $O\mathcal{E}_1$, equal to $O\mathcal{E}_2$, and at right angles to OD in phase. The E.M.F. applied to the primary must therefore be able to counteract $O\mathcal{E}_1$, to provide the voltage drop due to primary resistance, and to counteract the effect of the primary leakage. We have seen in the previous diagrams, how the primary current OC is obtained by compounding OC_o and OC_1, and it is this current which produces in phase with it the primary leakage flux N_1. As was the case in the secondary, the leakage flux produces at right angles to itself an E.M.F. which can be represented in magnitude and direction by Oe_1. The drop due to primary resistance is represented by OR_1, and by compounding $O\mathcal{E}_1$, OR_1 and Oe_1, as shown, we obtain OE_1, the E.M.F. which has to be applied to the primary terminals to produce OE_2 volts at the secondary terminals. In brief, the whole method of treatment consists in taking the secondary terminal E.M.F., compounding with it the secondary resistance and leakage drops to get the internal secondary E.M.F., which equals the primary internal E.M.F., and again compounding with this the primary resistance and leakage drops to get the primary terminal voltage. The leakage fluxes N_1 and N_2, both increase with the load, and it will be noticed that the more inductive the load is, the more nearly do the leakage E.M.F.'s add to the voltage required; as given by the compounding process. This is very noticeable in actual tests on transformers, the voltage drops on full non-inductive load being, say, 2 to 3 per cent., while on full inductive load it may be 6 to 8 per cent. or even more.

TRANSFORMER DESIGN.

Although the principle of action of a transformer is apparently such a simple matter, yet the design of a transformer to fulfil certain given conditions is *not* so simple as it appears. The chief electrical factors which influence the design are—

(1) The output.
(2) The ratio of primary and secondary voltages.
(3) The efficiencies at full, three-quarter, half, and quarter load.
(4) The no-load power factor.
(5) The permissible voltage-drop on full inductive load.
(6) The temperature rise allowed.
(7) The method of cooling employed, oil, air, forced draught, etc.

If the efficiencies at varying loads required on a transformer of known output are given, the magnitude of the copper and iron losses allowable can be at once determined, because the iron losses at the different loads may be assumed as constant, and the copper losses vary as the square of the load. Suppose one had to design a 100-kilowatt transformer which was required to have an efficiency at full load of 98 per cent., and at half-load of 97 per cent.

Let F be the iron loss and C the copper loss at full load,

the total loss at full load = 2 per cent. = 2,000 watts;

the total loss at half-load = 3 per cent. of 50 kilowatts = 1,500 watts;

$$\therefore \quad F + C = 2{,}000 \quad (1)$$
$$\text{and} \quad F + \tfrac{1}{4}C = 1{,}500 \quad (2)$$
$$(1) - (2) = \tfrac{3}{4}C = 500$$
$$\therefore \quad C = 666{\cdot}6 \text{ watts,}$$
$$\text{and } F = 1{,}333{\cdot}3 \text{ watts.}$$

From the iron loss allowable we can obtain a very good idea of the weight of iron necessary, because for each frequency, and with iron laminations of a given thickness, there is a flux density in the iron at which it is desirable to work, for if this density be exceeded, the loss is disproportionately large, and if a lower density be used, the iron is not being used to the best advantage. The value of this density for different frequencies can be obtained from the curves given in Fig. 364. Of course, in special cases, the no-load power factor may influence the density employed, as the use of a high density means a large magnetising current, and consequently a low no-load power factor. However, assuming that we have decided upon our flux density for the reasons given above, we can at once, from the curves, obtain the loss in watts per pound, and dividing this figure into the total iron loss, viz., 1,333·3 watts, we obtain the weight of iron to be used. This gives us the volume of iron, and the next consideration is what form the volume of iron should be given.

As we have seen, the most general variety, and the one possessing the most advantages, is the "core" type. We will therefore decide to adopt this, and then comes the question as to what section and dimensions we shall give the core. This is a matter for experience, the chief determining factors being the space at disposal, the method of cooling (this deciding the number of square inches of surface required to dissipate the watts lost), and the voltages in use. Of course, if the efficiencies demanded for both oil-cooled and air-cooled transformers are the same, it follows that one can make one of the oil-cooled type very much smaller in all ways than if it were air-cooled. The largest cooling area can be obtained by reducing the section of the core and making it long and thin, so that this construction would really be most advantageous for getting rid of the heat. However, this is limited by the necessity of having the transformer of a handy shape. The tendency is, therefore, to find the cores fairly long, the exact dimensions being fixed by experience. Another advantage of using a long core is that the length of the mean turn is considerably reduced, thus saving in copper and reducing the copper loss. Having selected dimensions for our cores which seem suitable, we can at once obtain a trial value of the total flux, N, by multiplying the area of the core by the flux density decided upon. The details of design are further touched upon at the end of Section VII.

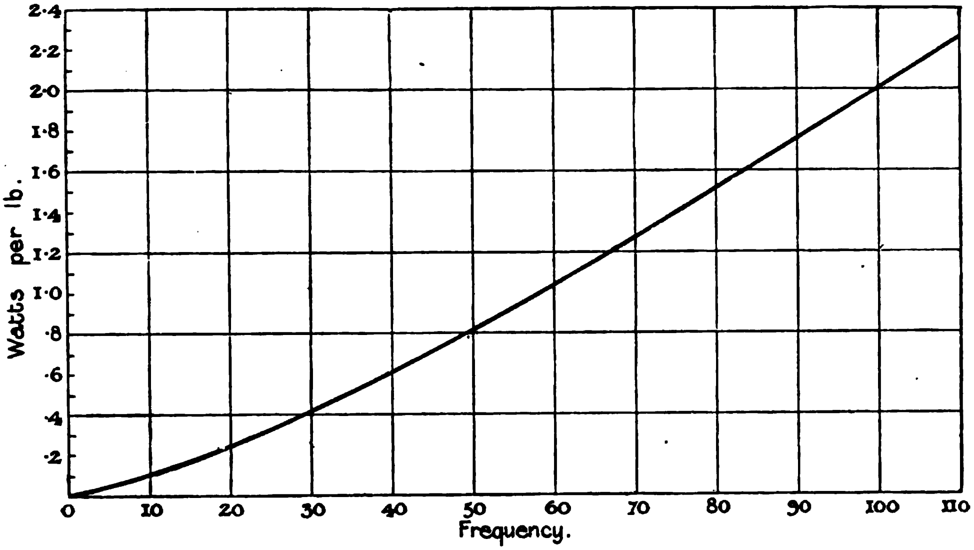


FIG. 364.—CURVE CONNECTING IRON LOSSES WITH FREQUENCY OF ALTERNATIONS.

SECTION VII.

DYNAMOS AND MOTORS.

CHAPTER I.—ELEMENTARY CONSIDERATIONS.

INTRODUCTORY—THE MAGNETIC CIRCUIT—LEAKAGE IN THE MAGNETIC CIRCUIT—COPPER CALCULATIONS—INSULATION.

THE elementary principle upon which the action of all classes of dynamo-electric machinery depends is that whenever a conducting material is moved so as to cut the lines of force of a magnetic field, an E.M.F. is set up in the conductor. The induction of currents in conductors when moved across a magnetic field has already been fully explained on page 230. We may also here at once state the converse, and say that when a conductor carrying an electric current is placed in a magnetic field, it will tend to place itself so that its own field coincides with that in which it is placed, and if movement is needed to effect this, it will move so as to cut the lines of force.

The action of any type of dynamo or generator of electric current is dependent upon the former conditions being fulfilled. Similarly, the working of an electric motor requires the fulfilment of the second condition. We are here stating the matter broadly, without reference to the *character* of the current which the generator delivers, whether continuous or alternating, and in the case of motors the same remark applies. Consider a single loop of conducting wire arranged to revolve upon its axis as shown in Fig. 365. Imagine pole pieces placed on the right and left of the loop, as in Fig. 368, and if the loop of wire is now revolved, we shall find that an E.M.F. is set up in each side of the loop, for if we carry wires from each of the sliding contacts shown in the sketch, and connect these wires to a galvanometer, we shall find that as long as the loop continues to turn a current will persist in the circuit, as shown by the galvanometer deflection. If we consider one side of the rectangular loop, it is obvious that in every revolution the magnetic field is cut twice, the conductor cutting the flux first as it leaves a N pole, and then again as it enters a S pole. We know from the laws of the induction of currents, that the direction of the induced current depends upon the direction of the magnetic flux, and the

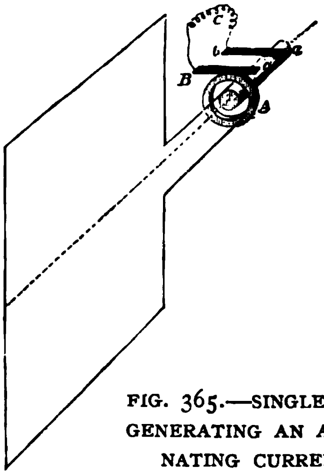


FIG. 365.—SINGLE LOOP GENERATING AN ALTERNATING CURRENT.

direction of motion; and thus it is obvious that the current induced in either side of the loop will *alternate* in its direction as the loop revolves, sending a current in one direction when it is cutting the flux from the N pole, and in the reverse direction when it enters the S pole region.

The current delivered to the outside circuit from this revolving loop will therefore change in direction twice in every revolution, and if the loop is revolved at a fair speed, an E.M.F. will be generated (and a current will flow if the circuit be closed) which changes from + to − and − to + many times in a second, in fact, an "alternating" current. This machine is a simple alternating current dynamo.

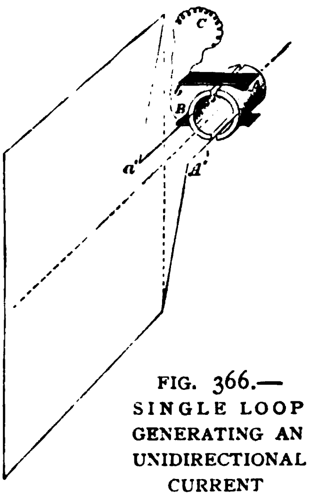


FIG. 366.—SINGLE LOOP GENERATING AN UNIDIRECTIONAL CURRENT

If we wish to obtain currents in one direction, or "continuous" currents, we must continually change the connections of the two ends of the loop to the two ends of the circuit C, making the change every time just at the instant when the current is about to reverse. This can be effected by connecting the two ends of the loop to a "commutator," which, in its simple form, consists of a metallic ring split longitudinally across the diameter, so as to form two insulated segments, which are each connected to one end of the loop, as in Fig. 366. Two strips of conducting material make contact upon this split ring at opposite diameters, in such a position that the circuit through the "brushes," as they are called, changes from one segment to the other at the moment when the loop is not cutting the flux between the poles.

A simple commutator of this description is shown in Fig. 367. The action is simple; by means of this mechanical arrangement we automatically change the connections to the loop, and the current in the external circuit continues to flow in the same direction while the loop revolves. This is the elementary type of the continuous current dynamo or motor, and in Fig. 368 we see such a simple machine represented with the field magnets *in situ*. We can conveniently represent the alternating current produced by our simple alternator in the form of a series of curves, as shown in Fig. 369. There the vertical lines represent to some scale the E.M.F. in the loop, and the horizontal line represents revolutions of the loop. In one revolution, as we have seen, the flux is cut *twice*, giving one + and one − wave. These waves represent the E.M.F. as rising in a gradual curve to a maximum value, and falling in

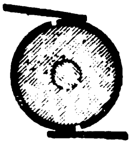


FIG. 367.—"SPLIT TUBE" OR TWO-PART COMMUTATOR.

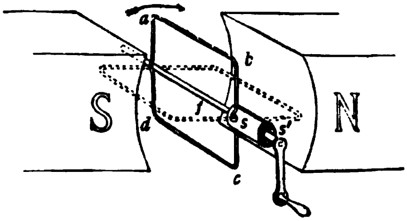


FIG. 368.—IDEAL SIMPLE DYNAMO.

the same gradual way, crossing the zero line, and then repeating the cycle.

If the magnetic field were evenly distributed at the pole faces, and if there were no other disturbing factors, we should obtain no such gradual curve. The E.M.F. would rise quickly to its maximum value, remain at this maximum during the whole time that one side of the loop was under a pole, and then fall abruptly to zero. Actually, as we shall see later, owing to the spread of the magnetic field at the pole face, and the effect of self-induction, no such sudden changes occur. The loop, before it comes actually under the tips of the poles, experiences the effect of a weak field, which induces a small voltage, and the density of the field in which the conductor moves gradually increasing, there results a wave of E.M.F. of approximately the shape shown, namely a "sine" wave.

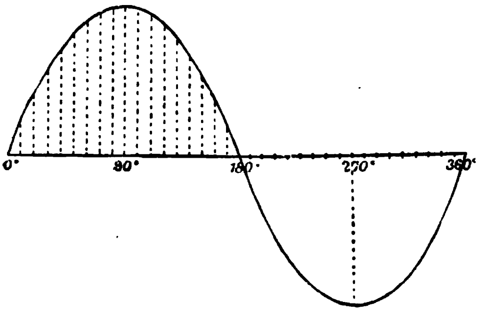


FIG. 369.—ALTERNATING E.M.F. FROM SINGLE LOOP IN UNIFORM MAGNETIC FIELD.

Fig. 370 enables us to understand the effect of the commutator in reversing the second wave, giving a unidirectional current, but it is hardly correct to call this a continuous current, because it will be seen that the E.M.F. pulsates in this case when we have only two segments or so, and at one instant approaches to zero. A *practical* dynamo provides a current in which the amount of this pulsation is practically nothing, for instead of employing two commutator segments, at least a dozen such segments are used, even in the smallest machines, and generally a very much larger number.

Fig. 371 shows the result of using eight commutator segments and four loops. The current never tends to die down to zero, owing to the fact that some of the loops are always active. In the diagram, the lower curves represent the induced voltages in the several coils, and the upper thick curve, the resultant of these.

It will be seen that there is very little pulsation in the voltage, and, as a matter of fact, there are other effects which tend to wipe out even such small pulsations as these, so that for all intents and purposes the E.M.F. is *continuous*, especially with the large number of segments generally employed.

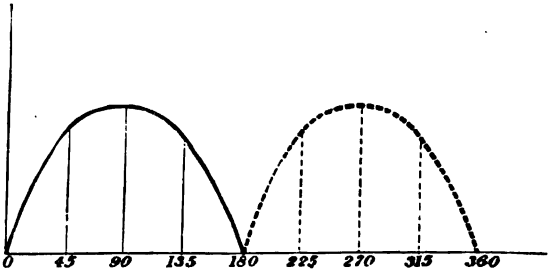


FIG. 370.—E.M.F. WAVE WITH TWO-PART COMMUTATOR.

Having now detailed the general principle of the action of dynamo machines, we should point out the apparent paradox, that the first dynamo, invented by Faraday

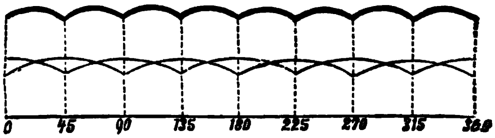


FIG. 371.—E.M.F.S OF FOUR PAIRS OF COILS IN SERIES.

in 1831, was a machine which gave continuous currents, but without the use of a commutator. Fig. 372 shows the construction of this machine: the edge of a copper disc was inserted between the poles of a powerful electromagnet, and Faraday found on revolving the disc that a unidirectional current could be produced if rubbing contacts were placed, one at the the periphery of the disc, and the other on the shaft, which was in metallic contact with the body of the copper disc.

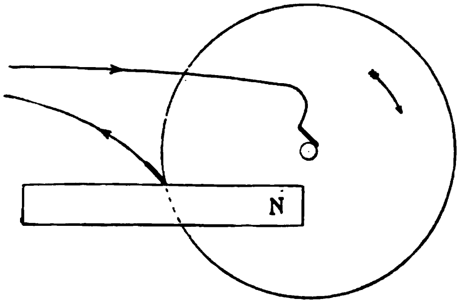


FIG. 372.—FARADAY'S DISC.

The currents in this case flow radially from the centre of the disc to the periphery, and as there is no reversal of the direction in which the conductor cuts the magnetic field, no commutator is necessary, the machine furnishing a perfectly steady, continuous current, the voltage depending upon the strength of the magnetism and the speed of the disc. At first sight it would seem that machines constructed on this principle would possess advantages over those employing commutators, but practically this is not so, as it is impossible to get any considerable voltage from a machine of this type except by the employment of very high speeds and very heavy field magnets, and though many attempts have been made to construct practical dynamos on this principle, they have only come into a very limited practical use. There is, however, some hope that in future such machines may have an increased application, and in Chapter III. we make some further reference to this type, called "unipolar" or "homopolar" dynamos.

THE MAGNETIC CIRCUIT.

The laws of magnetism and the calculations of the general magnetic circuit have been fully set forth in Chapter III., Section IV., but the demand of practice requires a few additional remarks.

As British units of length are adopted throughout this section, the magnetisation or permeability curves in Fig. 373 are plotted in *lines per square inch* and *ampere turns per inch* instead of the usual "B" (lines per square cm.) and "H" (the unit of magnetomotive force), and are representative of the materials as obtained in actual practice.

Variations in the quality of the material may in some samples cause some little variation in the permeability, but samples of commercial cast steel and sheet iron vary little from one another in their permeability.

Samples of cast iron vary considerably owing to the fact that manufacturers usually employ the ordinary foundry iron, which is not expressly intended for electrical use, as is the case with cast steel and sheet iron. The curves for sheet iron are plotted to both ampere-turn scales, A and B, enabling the permeability of the iron at high flux densities to be readily scaled off; the straight line showing the ampere turns required for $\frac{1}{100}$ inch of air is plotted to the scale A, the cast steel and cast iron curves corresponding to the same scale.

The calculation of the magnetic circuit of an actual machine is a comparatively simple matter, providing the quality of the steel or iron is well known and the leakage of the circuit be not considerably under or over estimated.

The accurate estimation of the excitation necessary for the air gap demands careful

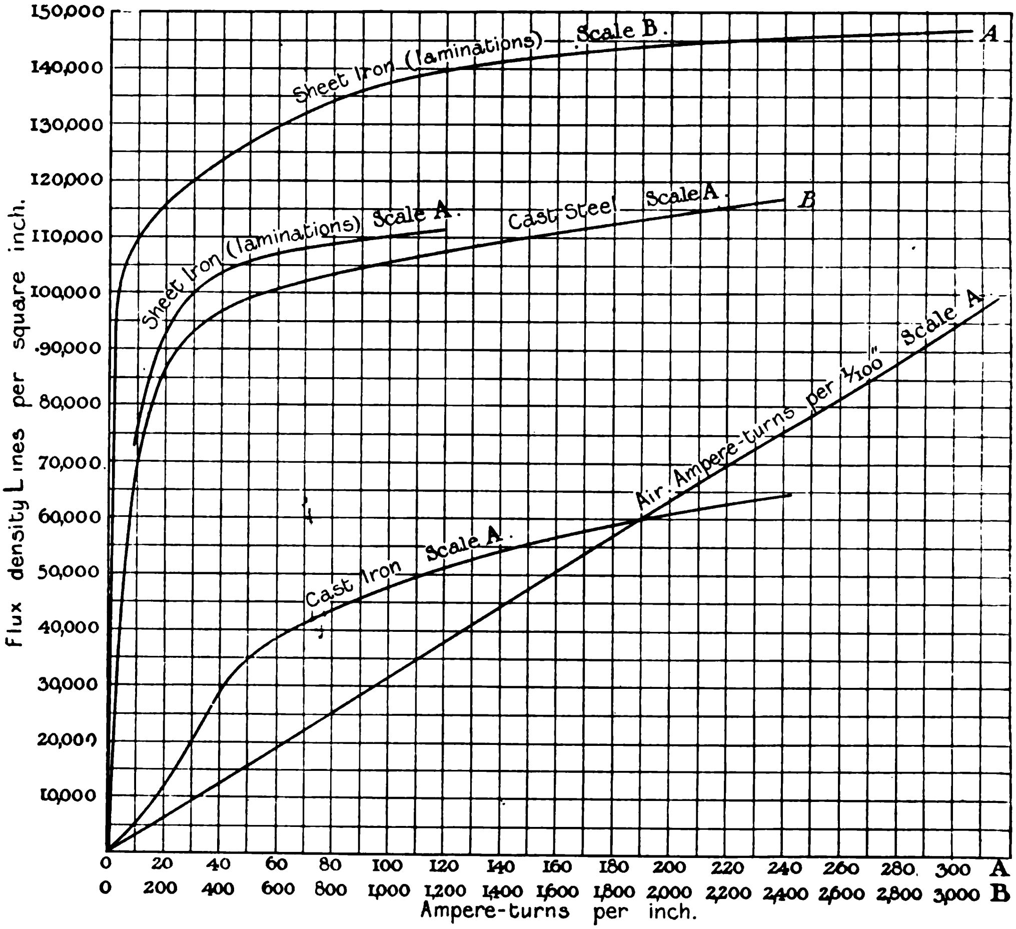


FIG. 373.—MAGNETISATION CURVES FOR STEEL, IRON AND AIR.

consideration, as in the magnetic circuit of continuous current machines and alternators the reluctance of the air gap is usually equal to or greater than the sum of the reluctances of the rest of the circuit.

Having been given the length of the air gap, it is necessary to estimate the *average magnetic density* of the flux in the gap, and as in all modern continuous current machines, and in the majority of alternators, the armature surface is slotted, the effect is to increase the mean density in the air gap compared with what the density would be if the armature presented an unbroken iron surface to the flux emanating from the poles.

As no simple rules can be given for this estimation, recourse must be had either to the rather complicated methods of Arnold and Carter, or, as is the case with many practical designers, to experience and common sense.

The calculation of the excitation necessary for the armature teeth again requires some judgment if they are highly saturated as is usually the case, especially with continuous current machinery, this being rendered necessary, as we shall see later, in order to prevent the distortion of the flux entering the armature. It is quite usual for the flux density in the teeth to reach a maximum apparent value of 140,000 or 150,000 lines per square inch (at roots of teeth), and in this case we must assume, and there is no doubt that it is actually so, that some of the lines *leak* down the sides of the armature slot, and do not thread through the iron.

Here also as in the case of the air-gap calculation, complicated methods exist for the estimation of the amount of this leakage, but these cannot be entered into here, and there is no doubt that more arbitrary and simple methods are resorted to by most designers.

LEAKAGE IN THE MAGNETIC CIRCUIT.

The flux entering the armature is, of course, always less than the flux existing in the poles and yoke of the machine, owing to the existence of leakage lines which do not cut the conductors on the armature.

Fig. 374 gives a good idea of the leakage lines in a bipolar machine. The whole of the flux generated in the field does not pass through the armature, for some of the lines from the field form local closed circuits, the flux composing these local circuits never entering the armature. In the old types of dynamo in which very long air gaps were employed, rendered necesssary by the use of surface wound (smooth core) armatures, the leakage was often very considerable, but nowadays, with the universal adoption of slot wound armatures and short air gaps (for economy in field copper) the leakage is much smaller. In the older machine the leakage co-efficient, defined as

$$\frac{\text{total flux generated}}{\text{useful flux in armature}},$$

was often 1·5 or more, whereas in modern continuous current machines, even in small sizes, the value seldom approaches this. The adoption of multipolar machines, except for very small motors of one or two horse power has also tended to decrease the leakage, and generally we may say that in a large multipolar machine the leakage coefficient will vary from 1·08 to 1·12, and in the four-pole machine will not exceed 1·15. In the smallest bipolar sizes the value should not exceed 1·2. In alternators, owing to the employment of generally longer air gaps, the values will range from 1·2 to 1·3.

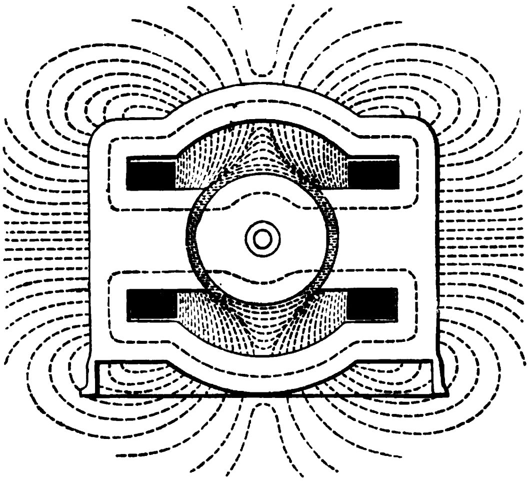


FIG. 374.—LEAKAGE FIELD OF IRON-CLAD DYNAMO.

In Chapter III. the calculation for the magnetic circuit of a six-pole continuous current generator is given in detail together with the saturation curve obtained on test. The calculation for the magnetic circuit of an alternator is to be made in a precisely similar manner.

COPPER CALCULATIONS.

Accurate data regarding the resistance, weight, and usual thickness of cotton insulation of standard copper wires is given in the table on page 422. The sizes of round wires

Gauge Number, S.W.G.	Diameter.			Cross Sectional Areas.	Current at 1,000 Amperes per Square Inch.	Ohms per 1,000 Feet.		Weight per 1,000 Feet.
	Bare.	Single Cotton, Covered.	Double Cotton, Covered.			15° C.	45° C.	
	Inches.	Inches.	Inches.	Sq. Inches.				lbs.
8	·160	·170	·174	·020106	20·106	·39784	·44645	77·440
9	·144	·154	·158	·016286	16·286	·49059	·55054	62·726
10	·128	·138	·142	·012868	12·868	·62473	·70107	49·562
11	·116	·126	·130	·010568	10·568	·75878	·84564	40·704
12	·104	·114	·118	·008495	8·495	·94078	1·05733	32·718
13	·092	·102	·106	·006647	6·647	1·2029	1·3499	25·603
14	·080	·090	·094	·005026	5·026	1·5908	1·7853	19·360
15	·072	·078	·084	·004071	4·071	1·9639	2·2040	15·682
16	·064	·070	·076	·003217	3·217	2·4856	2·7895	12·324
17	·056	·062	·068	·002463	2·463	3·2465	3·6435	9·4864
18	·048	·053	·058	·001809	1·809	4·4202	4·9607	6·9696
19	·040	·045	·050	·001256	1·256	6·3664	7·1448	4·8400
20	·036	·040	·046	·001018	1·018	7·8548	8·8152	3·9204
21	·032	·036	·042	·0008042	·804	9·9429	11·159	3·0976
22	·028	·032	·038	·0006157	·616	12·987	14·575	2·3716
23	·024	·028	·034	·0004524	·452	17·675	19·836	1·7424
24	·022	·026	·032	·0003801	·380	21·085	23·609	1·4641
25	·020	·024	·030	·0003142	·314	25·550	28·600	1·2100
26	·018	·022	·028	·0002545	·254	31·500	35·300	·9801
27	·0164	·0204	·0264	·0002112	·211	37·950	42·450	·8136

NOTES.

Specific resistance of copper = ·000000666 ohms at 15° C.
Weight per cubic inch ,, = ·3213 lbs.
Increase of resistance ,, = ·4 per cent. per degree C.

TABLE OF PROPERTIES OF COPPER WIRES—STANDARD WIRE GAUGE.

given are those usually employed in dynamo work. Sizes of wire smaller than a No. 16 are rarely employed in machines of any size, and larger wire than the No. 8 becomes unwieldy, and copper strip is resorted to for heavier sections. For strip windings for continuous current armatures, alternator armatures, etc., the copper is usually bent to shape by the manufacturer bare, and taped in a taping machine with cotton tape for use; though for armature work laminated copper strips are often employed, and in this case the conductor will be braided with cotton braid about 25 mils. thick, as the ordinary cotton covering is not sufficiently tough for heavy copper bars.

INSULATION.

The subject of insulation is one of paramount importance in dynamo-electric machinery, and it is a question which has been rather neglected in the past, but recently a considerable amount of attention has been directed to the matter, and a large number of reliable facts concerning insulating materials and their performance has been accumulated. The insulators used in the construction of electrical machines vary greatly according to the several purposes for which they are employed. It may be, of course, pointed out that such a thing as a perfect insulator does not exist, as from the very nature of an insulating material it must be to a large extent unmechanical. In the construction of electrical machinery, switchgear and accessories, various kinds of insulating materials have to be used under conditions which subject them to very different mechanical treatment. For instance, cotton tape impregnated with varnish serves as an excellent material for wrapping armature conductors, as in this case the material need possess very little mechanical strength, whereas when we come to the terminal bases or brush-spindle insulating bushes of the machine, we want an insulating material possessing mechanical strength in an eminent degree. For the commutator, material which will stand great compression without deterioration is necessary, and also it must wear well, as the friction between the brushes and the copper segments of the commutator necessarily wears the copper, and the insulation between the segments must wear at an equal rate. Up to the present one material alone, namely, mica, has been found to in any degree combine the necessary properties for the purpose. Moisture is a great enemy to effective insulation, and we may say that if a material is hygroscopic, it is useless unless the fault can be remedied by impregnation with some waterproof varnish, oil or wax. For low voltage work, the materials at hand have proved very satisfactory if used with discrimination, but when we come to the high voltages, which are quite common nowadays for alternating current work, ranging from 2,000 up to 20,000 volts, or even more, the question of insulation becomes of supreme importance on account of danger to life and breakdown, in case its strength should prove insufficient. Insulators may be roughly classified as follows:—

(1) Those occurring as minerals and used in their natural state, such as mica, marble, slate.

(2) Manufactured materials of a vitreous nature, such as glass, porcelain, and so forth.

(3) Those materials of vegetable or other organic origin, of which examples are cotton, silk, rubber, guttapercha, and the hard rubbers, vulcanite and ebonite, and a large variety of papers and cardboard, presspahn, manilla paper, etc.

There are a large number of special papers and cloths, mostly impregnated with varnish or linseed oil, which are very valuable, and compressed wood fibres are also used to a certain extent, but are apt to be hygroscopic. For all-round work a good insulator should possess the following properties:—

(1) Its resistance to spark puncture or or "*dielectric strength*" should be great.

(2) It should be strong mechanically, and preferably flexible: for other purposes a hard material which could be turned in the lathe would be more suitable. It should be unaffected by acid fumes, impervious to moisture, should not suffer chemical decomposition in ordinary use, and should be cheap. It should be pointed out that the *insulation resistance* of a material alone, that is, the resistance of a certain thickness in ohms, or millions of ohms, is not a good criterion of its suitability as an insulator. Many materials possess a high insulation resistance when dry, but are not able to resist the passage of a high tension discharge to any great extent. The behaviour of insulators is often very erratic, and experience, coupled with reliable tests on material can be the only true guide as to the suitability of a particular material for a particular purpose.

It must not be forgotten that the atmosphere itself may prove rather an erratic insulator if the voltage is sufficiently high. A high voltage discharge can creep over dusty or moist surfaces with ease, and whenever the atmosphere or leakage surfaces are depended upon for insulation purposes, great care must be taken to prevent the access of moisture to the surface of the insulator, and also to keep such surfaces clean. Dry air has an immensely high insulation resistance, but it is easily punctured by a spark discharge, in other words, its dielectric strength is low. Roughly we may say that 20,000 R.M.S. volts alternating will cause a spark to jump across an inch of air between needle points, but with continuous currents for the same effective voltage the sparking distance is less, but with high voltages we are almost entirely concerned with alternating potentials, continuous currents being not usually distributed at above 600 volts. In the table which we shall give at the end of this chapter, the data relate entirely to alternating current discharges.

If we contrast with the above the thickness of pure mica, which the same potential will pierce, we find from the average of a number of tests that 1 mm. ($\frac{1}{25}$ in.) of good mica will hardly be pierced by the voltage mentioned (20,000 R.M.S. volts), and with some samples a considerably higher voltage is necessary to puncture.

The dielectric strength of a sheet of insulating material is not constant for a given thickness. A given thickness of material will break down more easily if the given thickness is in a single sheet than when a number of sheets totalling the same thickness are used. Also, if a material is subjected to a high voltage for a prolonged period it will break down at a much lower voltage than if the test be only applied for a few seconds. This is in the main due to the fact that the dielectric becomes heated, due to the leakage of current through the material, and as in general the strength of insulators is impaired by a rise in temperature, the breakdown occurs at a lower pressure.

It must not be concluded, however, that in actual practice one can continuously subject an insulating material to anything approaching the voltage at which a test sample will break down. A large factor of safety must be allowed, and this factor will vary from 5 to perhaps 30, increasing as the thickness of the insulation decreases, and the liability to mechanical variation becomes greater. For instance, take the case of an alternator working at a pressure of say 4,000 volts; the experience of manufacturers shows that the micanite tubes which are used to line the slots which carry the windings of such a machine should be about $\frac{1}{10}$ in. thick. Now, average tests of $\frac{1}{10}$ in. micanite show that 1 mm. may be relied upon to stand for a considerable time upwards of 20,000 volts, showing a large factor of safety in the use of $\frac{1}{10}$ inch for that machine. A 500-volt continuous current armature is not considered well insulated unless there is quite 50 mils. (·050 in.) of the usual insulating materials, presspahn, tape, etc., between the copper conductors and the core. If we take the insulation to consist of 40 mils. of waxed presspahn, and 10 mils. of varnished tape, these together should stand quite 5,000 volts alternating current for a considerable time. When we come to very high voltages, it is impossible to allow for such factors of safety as these, and, in consequence, much greater care must be used in the selection of material and in manufacture. Even then the liability to break down will be considerably greater.

Mica is chiefly used in its natural state in the building of commutators for the small sizes, and is very satisfactory, but it is, however, very costly in large sheets, and therefore micanite often replaces the pure mica with satisfactory results for large commutators. Micanite is flaked mica pressed together with shellac varnish, and can be formed by moulds into any convenient form, and possesses the advantage that it becomes flexible when gently warmed, and micanite sheets can thus be bent by the manufacturer to form tubes or channels very easily. There is also a form of micanite which is flexible at ordinary temperatures, which is sometimes very convenient.

Slate is satisfactory for terminal boards and for switch bases and switch panels if free from metallic veins. It is hygroscopic, and is therefore often enamelled, but has fallen rather into disrepute for high voltages owing to the liability of the occurrence of the metallic veins mentioned.

White marble is extensively used for switchboards. It is free from metallic veins, and has a very good appearance, and does not absorb moisture.

Glass is not much used on machines or switch gear, obviously because of its brittle nature, though it is otherwise satisfactory.

White, well-glazed, and vitrified porcelain is used to a certain extent for insulating bushes on dynamos and motors, and extensively used on switch gear.

Rubber, in the vulcanised and unvulcanised form, is only used on the connecting cables. It is unsatisfactory and expensive for machine work, soon perishes, and is attacked by oil.

Silk is sometimes employed as a covering on thin magnet wires, but its cost prohibits its use, except for very small wires. In the form of tape it is excellent as a covering for copper conductors, but is rarely used, despite the fact that it is much thinner than cotton.

Cotton, either in the form of a yarn, as a covering for wires, or as tape, is very satisfactory when dry. It will absorb a large quantity of moisture, and is therefore impregnated with varnish when possible.

There are many excellent impregnated tapes or cloths on the market, such as Empire cloth, which is cotton treated with linseed oil, this material being sold in many thicknesses, both as cloth and canvas, ranging from 5 to 15 mils. in thickness. There are also obtainable certain cotton cloths backed with mica which are satisfactory, the cloth forming a good mechanical basis for the mica flakes. In cardboards and papers, we have the glazed cardboard, known as presspahn, which, if waxed, makes an excellent insulating material very suitable for slot lining.

Various kinds of paper are used, from the ordinary tissue paper, 1 or 2 mils. thick, which is used as an insulation between armature discs or transformer stampings, to the heavy, tough manilla, Willesden, or cartridge paper; oiled paper also is sometimes used. Papers made from linen, partaking of the nature of banknote paper, are very good, being very tough and uniform in thickness. Thin paper, as a substratum, with thin flaked mica pasted on is used, being similar to the mica-cloth previously mentioned. There are a number of hard homogeneous materials known under various trade names, such as "ambroin," "isolit," etc., extensively used for bushes, insulating washers, and small parts, which have great mechanical strength and hardness, can be readily machined, take a high polish, and which generally partake of the nature of ebonite. These have largely replaced the more expensive insulating materials, both on the score of expense and on account of their more enduring properties.

The table of insulating materials which we give is derived from various sources and gives the results of tests on different materials commonly used in machine construction.

The importance of the length of application of the voltage is well shown by some of the data in this table. It will be noticed that in some cases the different puncture voltages are given, the first, the higher applied voltage, puncturing the insulator after a short interval, while a lower pressure sufficed to puncture if the time of application was longer. It is important to note in this connection that the maximum values of alternating voltages do not bear an invariable ratio to the R.M.S. values, but that the ratio depends upon the wave form. A flat topped wave will be less exacting on the insulation than a pointed one of the same R.M.S. value.

TABLE OF PROPERTIES OF INSULATING MATERIALS.

MATERIAL.	THICKNESS AND NUMBER OF LAYERS.	CONDITION.	DISRUPTIVE PRESSURE IN VOLTS.	REMARKS.
Air	½"	—	12,000	Tests made between needle points.
"	1"	—	20,000	
"	4"	—	55,000	
Mica	·004" (4 mils.)	—	11,500	Untreated mica in natural state.
"	·040" (40 mils)	—	61,000	
Micanite	·004"	—	4,000	—
"	·040"	—	24,000	—
Flexible micanite	·004"	—	3,000	—
Thin oiled paper	·100" (56 layers)	—	16,000	Broke down in 3¼ minutes.
Thick oiled paper	·100" (26 layers)	—	12,000	Broke down in 30 minutes.
Paraffined press-pahn	·100" (9½ layers)	—	11,500	Broke down in 25 minutes when paraffin boiled out.
Paraffined press-pahn	" "	—	26,000	Broke down in 1 minute.
Fuller board	·040"	As received	7,000	—
" "	"	Dried out	8,000	—
" "	"	Varnished	14,000	—
Tape, treated with standard varnish	·100" (13 layers)	—	13,900	Broke down in 35 minutes.
Tape, treated with standard varnish	"	—	15,500	Broke down in 2 minutes.
Linen tape untreated	·100" (many layers)	—	2,600	Broke down in 6 minutes.
Oiled linen	·100"	15° C.	5,000	—
" "	"	60° C.	4,500	—
" "	"	100° C.	3,800	—
Empire cloth	·010"	—	3,000	—
" "	·020"	—	5,400	—
" "	·040"	—	10,000	—
Red fibre	·022"	Unheated	1,300	—
" "	"	After heating to 75°–100° C.	4,000	—
" "	"	After heating to 100°–125° C.	4,350	—
"	"	After heating to 125°–150° C.	3,950	—
"Ambroin,"	·200"	—	Not pierced by 3,600	Quality of "ambroin," A.F.

CHAPTER II.—THE DESIGN OF CONTINUOUS CURRENT MACHINERY.

THE ARMATURE—BRUSH GEAR AND BRUSH HOLDERS—ARMATURE WINDINGS—COMMUTATION—HEATING—COMMUTATOR HEATING—FIELD HEATING.

As we have seen in the preceding chapter, the ideal simple dynamo, consisting of a conducting loop and two-part commutator arranged to revolve in a bipolar magnetic field, has to undergo very considerable modifications in order to fit it to the needs of a practical machine. In a machine of any size a much larger number of commutator segments must be used, and instead of the single loop, a number of turns, suitably connected to the commutator bars, are necessary.

The continuous current machine, whether it be a dynamo or a motor, will consist then of the following essential parts :—

(*a*) The field system, generally stationary, consisting of a mass of iron, the magnetism of which is maintained by means of a coil or coils of insulated wire supplied with exciting current from the machine itself, but occasionally from an external source.

(*b*) The armature, consisting of coils of wire wound on, or embedded in, a core of laminated iron, the iron core being necessary in order to carry the magnetic flux into and through the coils with as small an expenditure of magnetising force as possible.

(*c*) A commutator, which serves to collect and commute the currents in the coils, the collection being effected by fixed contacts pressing on the face of the commutator. These contacts are usually termed brushes, owing to the fact that in the early days they took the form of a copper or brass brush. Nowadays the "brush," in all but exceptional circumstances, takes the form of a hard carbon block mounted on a suitable metal holder.

When the dynamo is run up to speed, a small initial current is generated in the armature, due to the fact that the field magnets always possess a small amount of permanent magnetism, and this sends a correspondingly small exciting current through the magnetising coils. This results in an increased magnetic field, which in turn generates a higher voltage in the armature, and hence a more powerful exciting current flows, and so the magnetism of the field and the voltage of the machine is built up to its full value. A limit is reached in magnetism and voltage when the iron becomes so highly magnetised that any further increase would require a greater magnetising force than the armature can supply (under the given conditions of speed, etc.) without a more than equivalent loss.

There are two general ways of connecting the field coils with the armature :—

(*a*) The shunt connection.

(*b*) The series connection.

Fig. 375 shows the shunt connection It will be seen that the two ends of the field winding are connected straight across the terminals of the armature, and, as the full voltage of the armature is available on these coils, they must be wound with a suitable size of wire, so that, automatically, the right amount of current passes through to provide the correct amount of excitation. In the series method of connection, shown in Fig. 376, only one end of the exciting coil is connected to the armature, the other end forming one of the main terminals of the machine, the other armature terminal forming the second. In this case therefore the whole current from the armature passes through the series coil, and it must be so designed as to be able to carry the full current continuously, at the same time providing the requisite excitation. Figs. 377 and 378 illustrate the "compound" method of winding, a combination of the series and shunt methods, the shunt winding remaining substantially as before, while at the same time a few turns of series winding, through which the whole current of the armature passes, are added. This arrangement enables the dynamo to maintain more constant voltage at its terminals under varying conditions of load than would be possible by using either method of winding separately; and, conversely, in a motor, it enables the machine to maintain more constant speed.

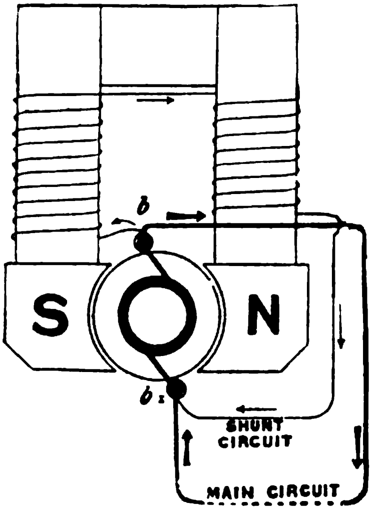


FIG. 375.—A SHUNT DYNAMO.

Coming now to the forms and methods of construction adopted for the field magnet system, we find a great diversity in constructional detail.

Fig. 379 shows a number of multipolar field systems by the Crocker-Wheeler Co. The yokes are of cast iron, solid wrought-iron poles being cast welded into the yokes. Many different types of field construction have been employed, but the choice of the most suitable method of construction depends largely upon factory conditions, it being generally entirely a question of cost as to which method of construction the preference is given. Steel castings are very satisfactory if the machine is of sufficient size; but for very small machines steel castings are inadmissible, owing to the fact that in a thin steel casting it is difficult to get a sufficiently homogeneous mass of metal.

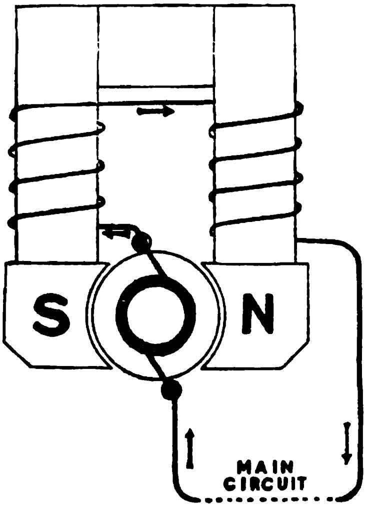


FIG. 376.—A SERIES DYNAMO.

The permeability of cast steel is high, and consequently field frames in cast steel are made much lighter than they would have to be if of cast iron; but, despite this fact, cast iron has been used extensively for all types of machines; but the *pole cores*, around which are wound the exciting coils, can never, except in the very smallest machines, be made of cast iron, owing to the greater length of mean turn of wire and hence greater weight of copper required to produce a given flux through the poles. For small motors of one or two horse-power, however, it pays to use a single casting of cast iron for the yoke and poles, the extra weight of copper required being more than compensated for by the reduced labour costs and the general simplification of the design.

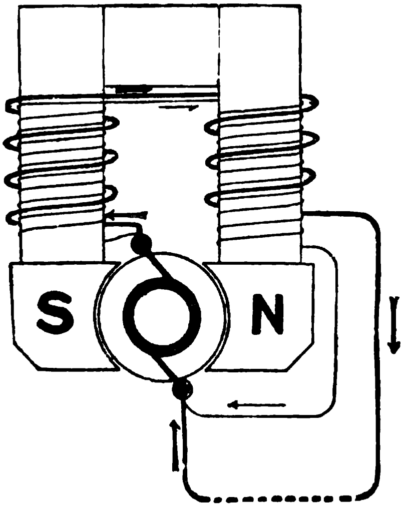


FIG. 377.—SERIES AND SHORT-SHUNT COMPOUND WINDING.

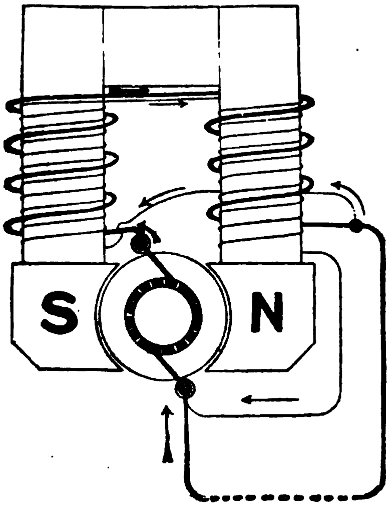


FIG. 378.—SERIES AND LONG-SHUNT COMPOUND WINDING.

A good construction is to employ a heavy cast iron yoke with pole cores of sheet iron bolted on, the cores being built up of stampings stamped to the exact size required for the pole, and the stamped sheets being then riveted together. It is advisable, in large machines employing this construction, to provide a rectangular hole through the pole for the insertion of a steel bar to receive the bolts from the yoke. This gives a much better hold than the bolts would take in the laminated pole core and conduces to rigidity.

The permeability of cast iron is only 30 to 40 per cent. of that of cast steel, and hence for a given total magnetic flux we must employ nearly two and a half times the weight of cast iron in the yoke compared with that which would be necessary with cast steel; the low price of cast iron, however, makes up for its low permeability.

A construction frequently followed is to attach the poles to the yoke by "casting in." Figs. 380 and 381 illustrate a large multipolar field magnet by Messrs. Dick, Kerr; the former shows the built-up laminated poles in the foundry bed ready for the pouring of the yoke, and the latter the complete yoke with some of the poles wound, and with the terminals in place. With proper precautions to ensure a good metallic joint between the poles and yoke in casting, this method is very satisfactory. In machines in which solid pole cores are used it is usual to employ a laminated pole tip in order that the eddy current losses, which occur in solid pole faces when the air gap is short, shall be reduced as much as possible. A pole tip of some kind is generally used in all except the smallest machines, for two reasons: firstly, to give a larger sectional area to the pole face, in order to reduce the magnetic density in the air gap; and, secondly, in order that the length of the pole arc shall be a considerable proportion of the pole pitch. If this were effected by making the whole core of such sectional area, the weight of copper needed in the exciting coils would be unduly increased, and there would be difficulty in finding room for them. Other disadvantages are pointed out below. In practice the best results are obtained when the ratio of pole arc to pole pitch is about 70 to 75 per cent. If we employ a very short pole arc the magnetic density in the air gap would be very high, and consequently, not only would the excitation for a given length of air gap be large, but we should not be utilising the maximum peripheral surface of the armature, and the output or the machine would be reduced. The proportion of pole arc to pole pitch also has a direct connection with the capability or the machine to run sparklessly at all loads without any movement of the brushes round the commutator. This important point will be treated of more fully when commutation is dealt with generally.

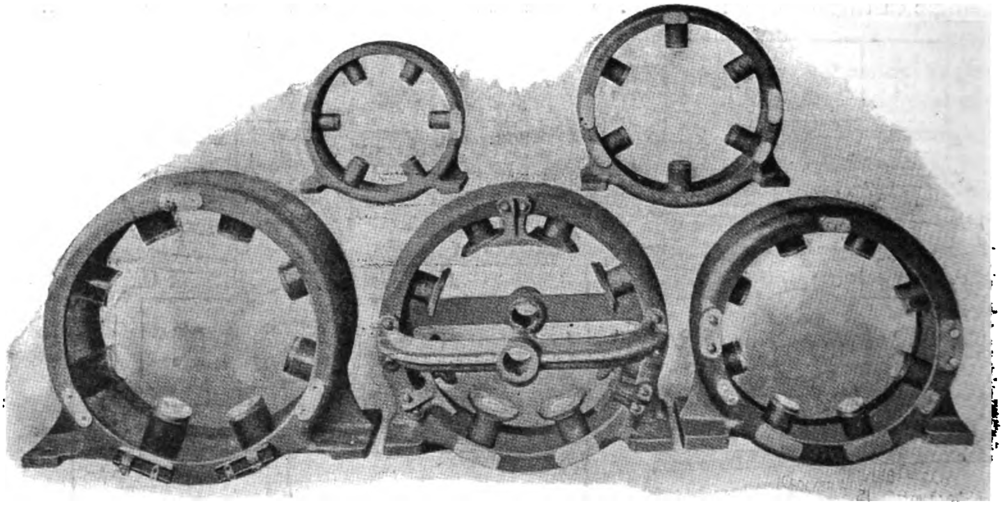


FIG. 379.—TYPES OF MULTIPOLAR FIELD SYSTEMS.

THE ARMATURE.

Fig. 382 shows the various stages in the construction of a small Bruce-Peebles four-pole armature.

In all modern machines slots are formed in the armature core, the coils being placed in these and so protected against mechanical injury. Formerly the armature core consisted of a smooth iron cylinder, on the surface of which the coils were held, these being known as "smooth core" armatures. This type of armature was very expensive to wind, was mechanically inferior to the present slotted type, and had other disadvantages which tended to make the machine generally much more expensive.

The armature is always built up of a large number of thin discs of iron, the discs being lightly insulated from one another by means of varnish or tissue paper. This lamination of the core is necessary in order to avoid the generation in the iron itself of eddy currents, which

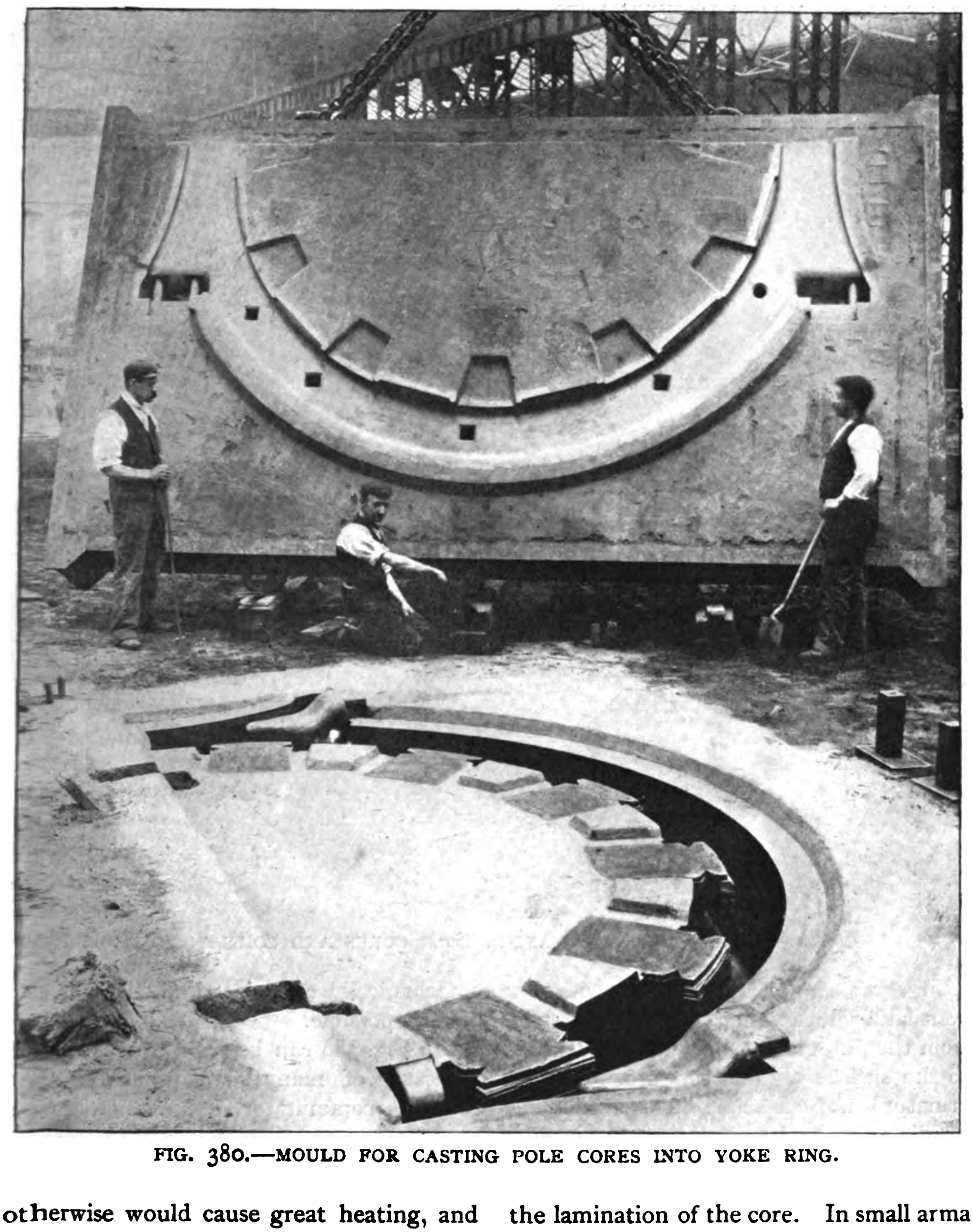


FIG. 380.—MOULD FOR CASTING POLE CORES INTO YOKE RING.

otherwise would cause great heating, and a large loss in energy. As we shall see later, there is also a further loss due to hysteresis taking place in the armature core, which, however, is independent of the lamination of the core. In small armatures such as the one illustrated, it is a simple matter to obtain a good strong mechanical construction, to make suitable provision for a certain amount of ventilation through the core, and to arrange stout end plates which serve the double purpose of supporting the overhanging ends of the armature coils and clamping the laminations after they have been threaded on to the shaft.

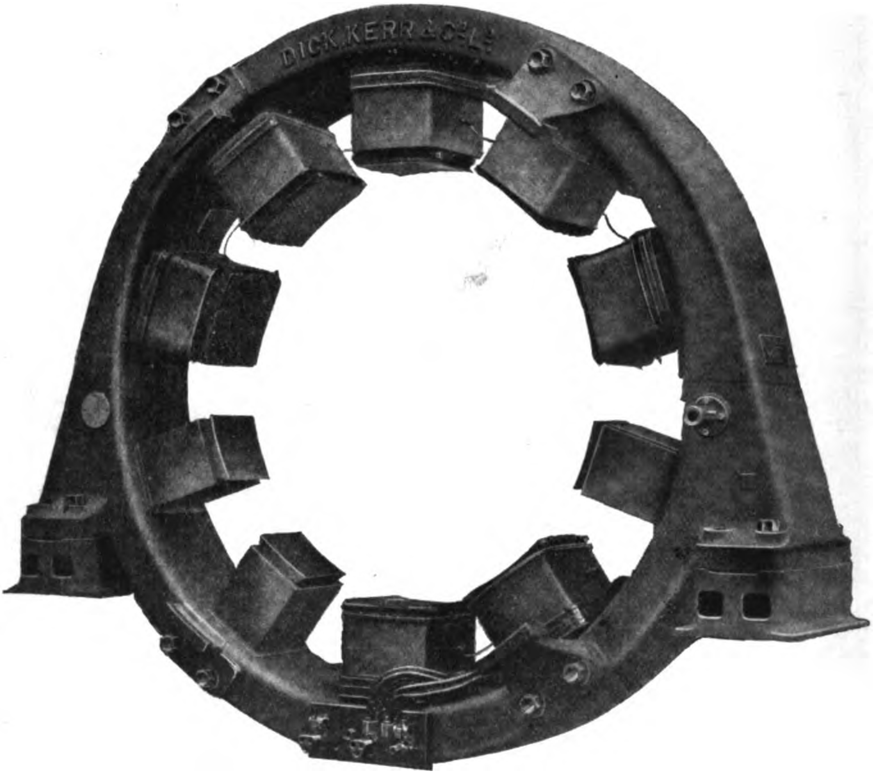
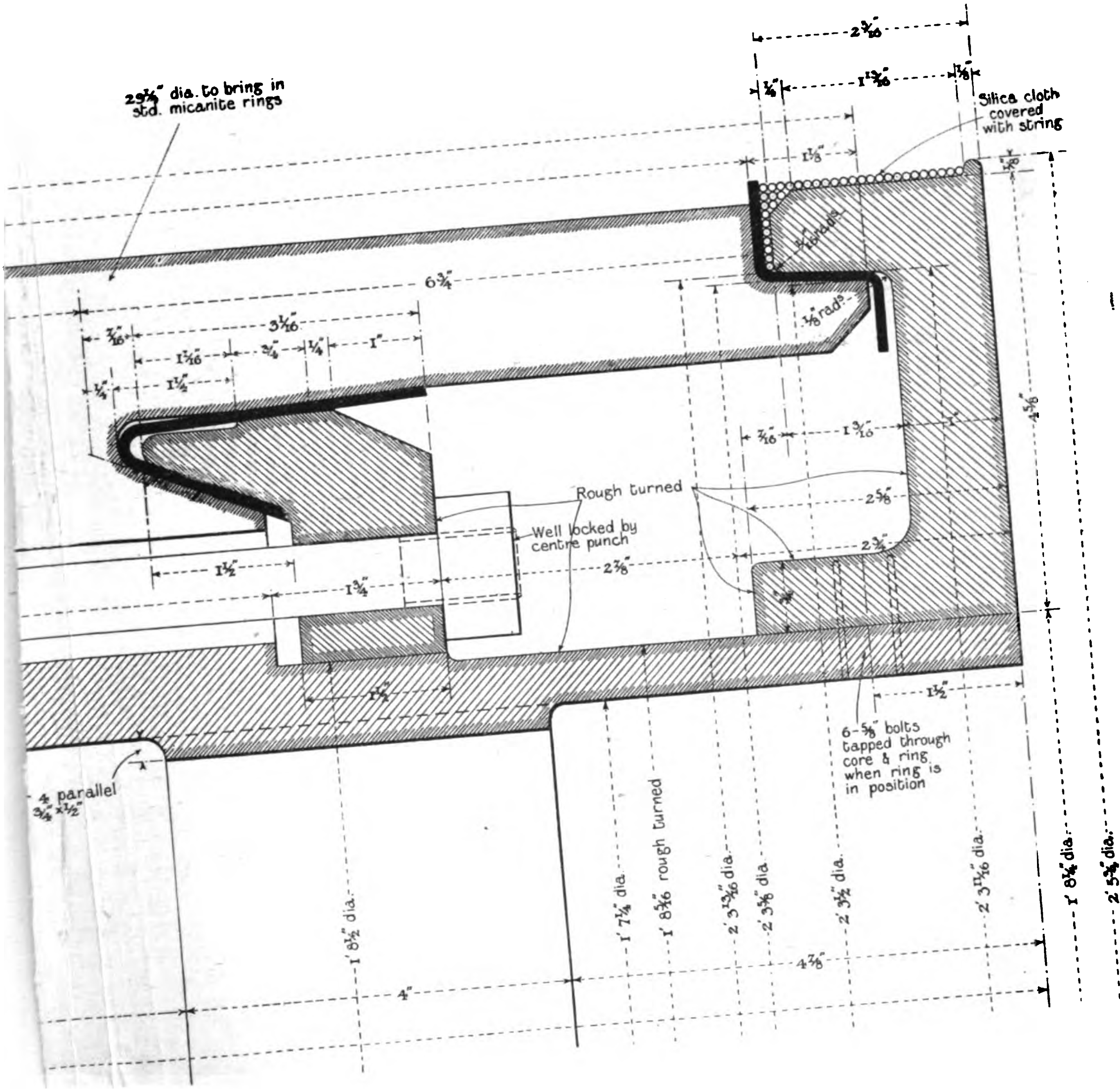


FIG. 381.—YOKE RING WITH CAST-IN POLE CORES AND COILS IN POSITION.

Fig. 383 shows an armature with one ventilating duct, which serves to carry air from the holes in the discs next to the shaft to the surface of the armature. In small armatures not exceeding six or seven inches in diameter it hardly pays to provide ventilating ducts through the core, as the outside surface is sufficiently large to dissipate the heat generated ; but in large armatures the efficient ventilation of the core by numerous and well arranged ventilating apertures is of supreme importance. Examples of large armatures, and further details as to the methods adopted to ensure their effective ventilation, occur in Chapter III.

The commutator is one of the most vital parts of the armature, and great attention must be bestowed upon it to ensure that mechanically and electrically it is as perfect as possible.

In Fig. 386 can be seen a modern commutator of many parts. Each segment of the commutator consists of a deep copper bar electrically insulated from its neighbours by thin strips of mica or micanite, this material being universally used, as it is found that no other substance combines to an equal extent the necessary properties of good electrical insulation and the proper mechanical strength and hardness, the wear of good mica being



NSTRUCTION COMPANY. (*See page* 433.)

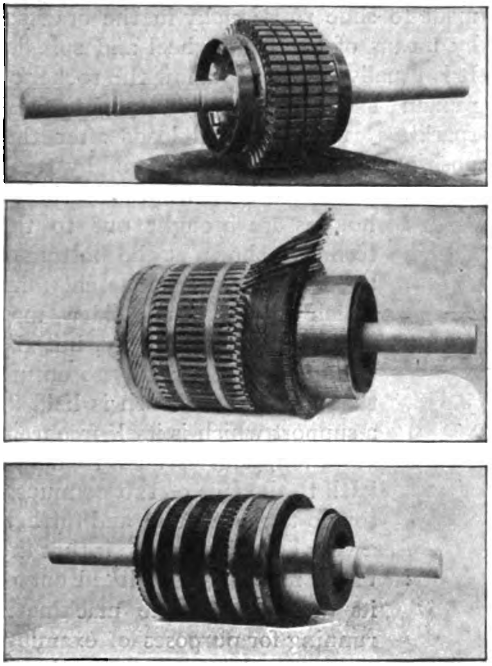


FIG. 382.—THREE STAGES IN THE WINDING OF AN ARMATURE.

approximately equal to that of hard drawn copper, as we have already pointed out in Chapter I.

Plate I gives a sectional view through the commutator of a 500 kilowatt E.C.C. motor generator. The segments are tightly held between the commutator bush and a **V**-ring, and are tightened by bolts spaced round the periphery. The micanite end rings which are employed to insulate the segments as a whole from the bushes are shown as thick black lines.

It is very necessary that the segments, after having been assembled into a loose ring, with the mica insulation between each, should be thoroughly compressed before being placed in the lathe for the purpose of turning the interior periphery and the **V**-grooves for the reception of the clamping rings; otherwise trouble with loose segments is bound to occur.

The segments can either be inserted into an assembling ring such as is shown in Fig. 384, consisting of a solid ring, inside of which are a number of loose segments of a cylinder, and compressed by tightening up the set screws threaded through the external ring as shown in the figure, or a special hydraulic press as shown in Fig. 385, can be utilised for the same purpose, the press serving to force the segments into the interior of a steel ring.

In both cases the segments while thus held have the **V**-grooves turned in each end and are then gripped between the bush and **V**-ring, and the external ring removed.

In the former case, the outside ring is heated up to above 150° Fahr., which, by its subsequent contraction when cooling,

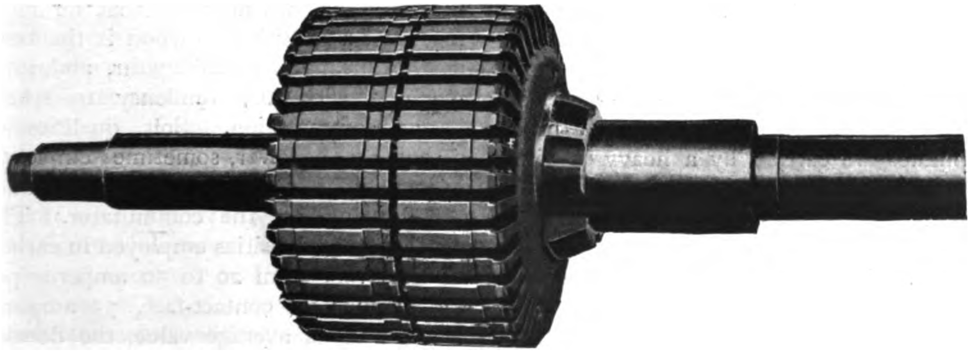


FIG. 383.—UNWOUND ARMATURE CORE ASSEMBLED ON SHAFT, SHOWING VENTILATING DUCT IN THE CENTRE.

materially assists by adding to the pressure already exerted by the tightening up of the set screws.

BRUSH GEAR AND BRUSH HOLDERS.

Examples of several types of modern brush gear are illustrated in the next chapter, and it is only necessary here, therefore, to enumerate the essential conditions which determine the design of the brush holders and brush gear. Fig. 386 illustrates a sixteen-pole dynamo by Messrs. Dick, Kerr & Co., and shows clearly the brush gear, there being sixteen brush sets, each with six brushes. In this example the brush spindles are carried by a heavy cast-iron ring, called a rocker ring, encircling the commutator, the ring being held in position by brackets bolted to the magnet frame. As the brushes must be capable of being moved through a small angle, in order to ensure that the collection of current takes place in the best position for sparkless commutation, the rocker ring is made to slide rotationally in the brackets by means of the hand wheel and spindle. It is usually possible to allow the rocker to remain fixed in the best position for sparkless running at all loads after this position has been determined by test. The collecting cables from the brush holders are brought out to the terminals shown at the bottom of the machine. The actual form which the brush holder may take varies considerably, but the essential point is simply to ensure that the carbon brush is held in a support which is itself free from vibration, and is able to adjust itself to the face of the commutator, to take up wear; and further, a very desirable feature is that the brush may be easily lifted out of its holder while the machine is running for purposes of examination or replacement. A suitable pressure is provided for, generally by varying the tension of a spring. Good electrical contact between the carbon block and the brush spindle is necessary, and this is often provided for by embedding in the carbon block, during the process of moulding, a flexible copper connection.

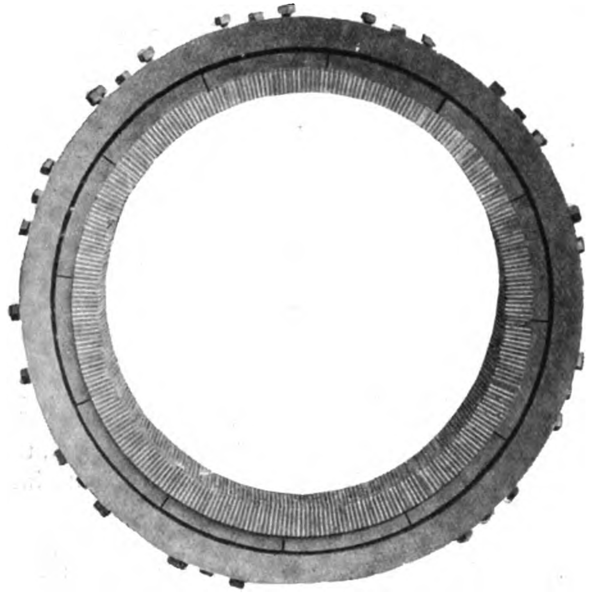


FIG. 384.—COMMUTATOR PARTS HELD IN CLAMPING RING READY FOR TURNING V-GROOVES.

As regards the kind of carbon which is most suitable, we may say that for most machines a fairly hard carbon is the best, as this means less rapid wear, and, in a machine with any tendency to spark, better commutation. Soft qualities of carbon are, however, sometimes employed in low voltage machines in order to reduce the heating on the commutator. The usual current densities employed in carbon brushes vary from 20 to 50 amperes per square inch of contact-face, 35 amperes being a good average value, the density permissible depending upon the quality of carbon, the hard carbons generally having a low conductivity, and permitting of not more than 30 amperes per square inch, while with the soft carbons this value can be pushed in favourable circumstances up to the upper limit mentioned.

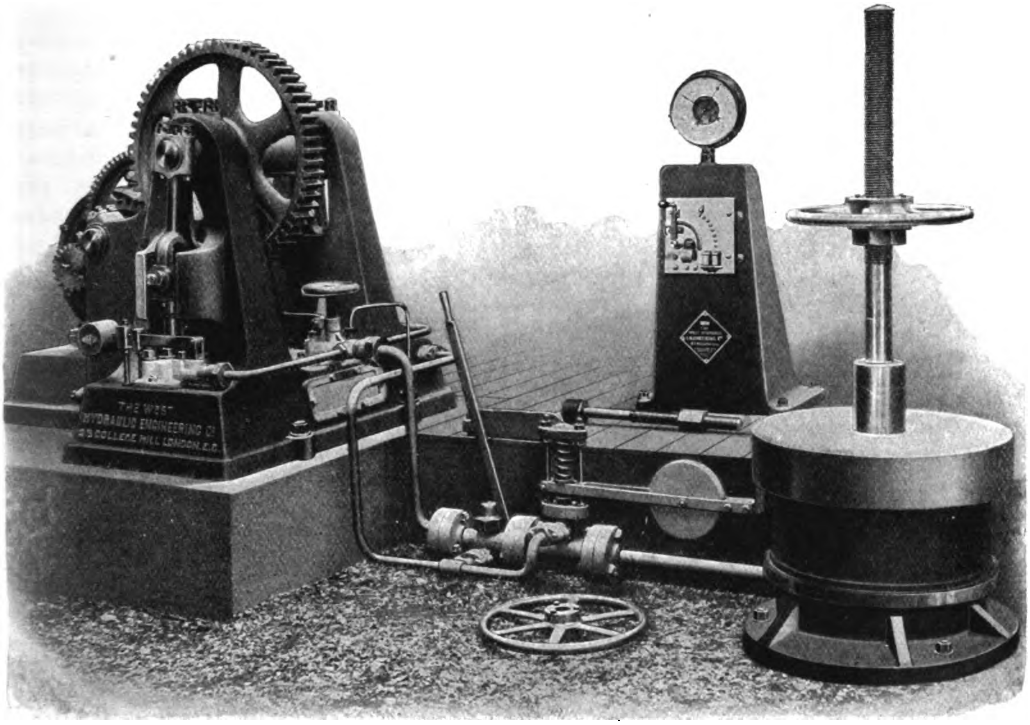


FIG. 385.—HYDRAULIC COMMUTATOR PRESS.

ARMATURE WINDINGS.

An armature has to carry a definite number of conductors, depending upon the speed, the voltage which must be generated, and the amount of flux which the field system can provide in relation to the number of poles.

We have already seen in a preceding chapter of this work that a single conductor cutting 10^8 magnetic lines a second will generate one volt, and from this simple statement of fact the necessary number of conductors which will have to be placed in the armature can be deduced in any given case. The simple expression connecting the speed of an armature, the volts generated, and the quantity of flux cut will be stated in the next few pages, but it is necessary first to consider the various ways in which the armature conductors can be connected up to form definite circuits through the armature.

The simplest form of armature winding, and one which was much used in the early days, is the "ring" winding. An annular core of iron, built up of thin rings, or even of wire, was used as the core, and around this, as shown in Figs. 387 and 388, the coils were wound as a continuous winding closed upon itself. From suitable points connections were taken to the commutator. Very often the ring winding was a surface winding, but sometimes the windings on the outside surface of the ring were sunk in slots.

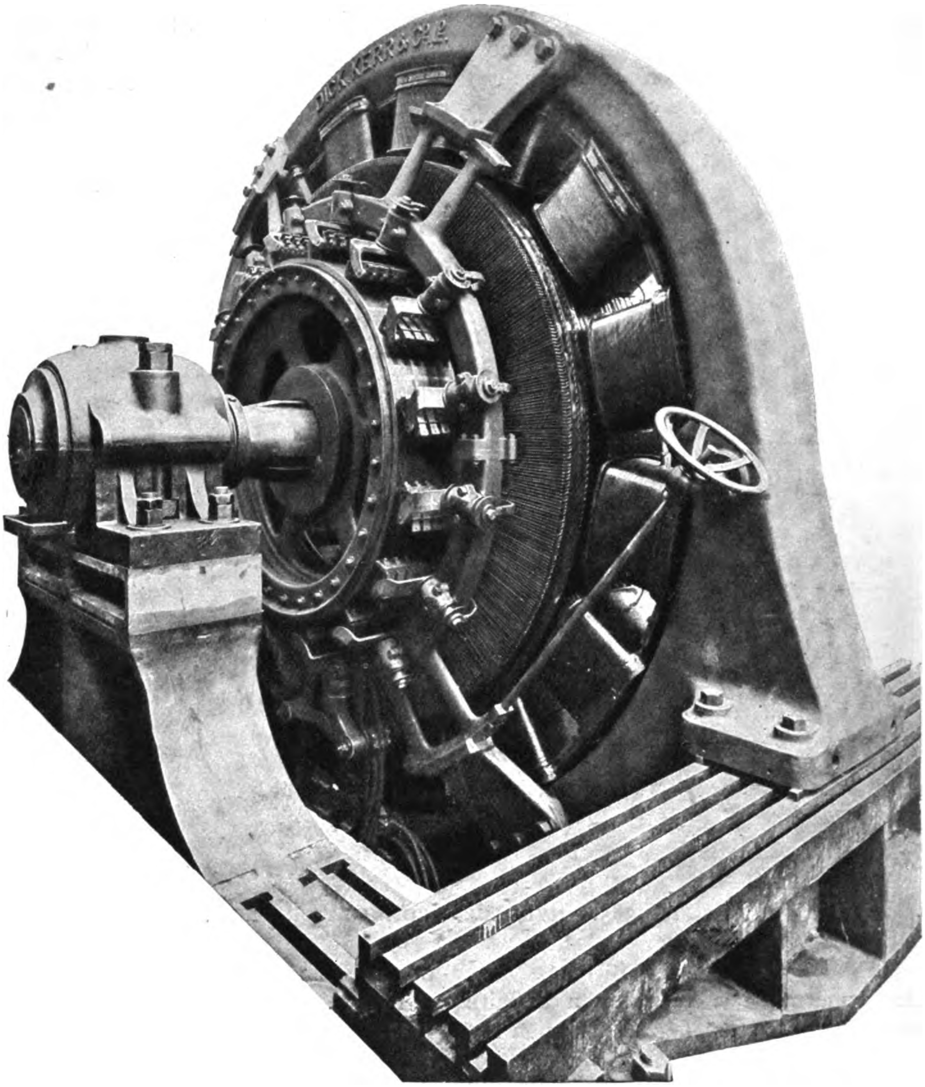


FIG. 386.—SIXTEEN-POLE D.C. GENERATOR SHOWING BRUSH GEAR.

This winding is rarely used now, except on special high voltage dynamos designed for lighting electric arc lamps, where it has certain advantages as regards ease of insulation, but it must be considered, for general purposes, as obsolete. This is the most simple winding to understand, the more usual modern windings about to be described being at first sight more complicated, though identical in their action.

In the "drum" winding, which is now universally used, the conductors are wound as on the surface of a drum, as shown diagrammatically in Fig. 389, there being no conductors which pass through the hollow interior of the armature core. Drum windings are divided into two classes—first the "lap" windings, formed of coils, in which each coil laps over its neighbour, the winding gradually progressing round the armature from slot to slot. Secondly, the "wave" windings, in which the winding zigzags round the armature, with continuous forward progression; from this property deserving the appellation of "wave."

The essential differences between the "lap" and "wave" windings are easily seen by a comparison of Figs. 390 and 391.

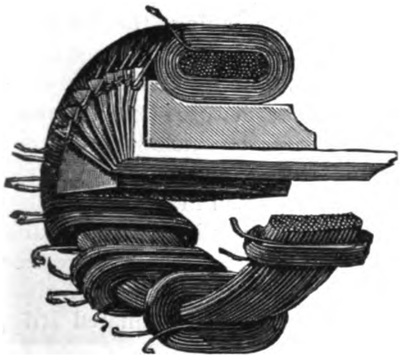


FIG. 387.—SECTION OF EARLY FORM OF RING ARMATURE.

The thick lines across the pole faces in the diagrams may be considered as representing slots in the armature with one bar lying in each slot. In each case, of course, the winding "steps" across a pole pitch, or practically so, and in the case of the lap connection the winding is brought back to the slot next but one to that at which it was started, and then continues round the armature in this fashion until all the slots are filled up, the winding thus forming a closed circuit through the armature. The connections to the commutator would be taken out from points at the ends of the bars all above or all below the poles in the diagram.

In the wave winding, the winding spans over a pole pitch as before, but the turn, instead of doubling back, continues to progress round and round the armature until, when all the slots have been filled up, a closed circuit is obtained through the armature as in the case of the lap winding.

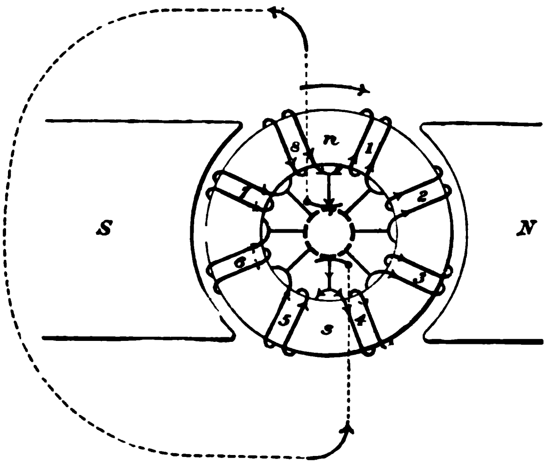


FIG. 388.—WINDING DIAGRAM OF ELEMENTARY BIPOLAR RING ARMATURE.

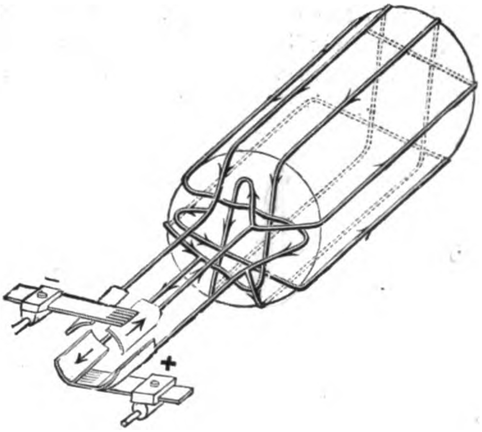


FIG. 389.—FOUR-COIL DRUM WINDING.

The constructional difference between the lap and wave windings can be easily explained by referring to the large armature shown in Fig. 392.

It will be noticed that a number of coils or turns of conductor have been placed in the slots, and at the commutator side of the armature the ends of the different turns are ready to be bent for connecting to the commutator. In the case of the lap winding the ends of the bars will be bent *inwards*, similarly to those at the opposite end of the armature, while for a wave winding the ends will be bent *outwards* in order that the winding may zigzag round the armature.

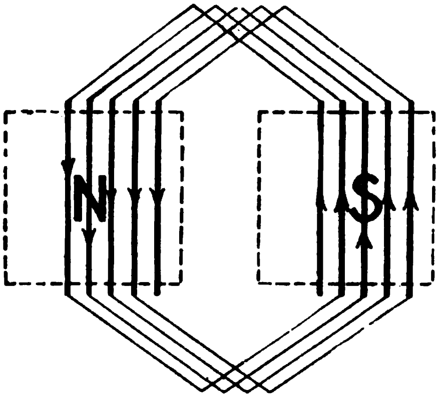


FIG. 390.—LAP WINDING.

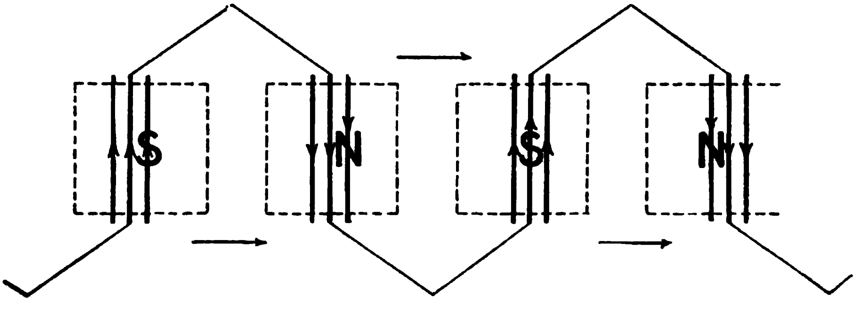


FIG. 391.—WAVE WINDING.

We have referred to the surface or smooth core windings as obsolete, and therefore need only consider the various ways in which the turns of the winding may be grouped together in the slots in the armature core.

The armature has to carry, as we have seen, a definite number of conductors, depending upon the proportions of the machine and the specified speed, voltage, and output, and the kind of winding, whether lap or wave, in relation to the number of poles; and as we cannot connect less than one turn of winding to each commutator bar, it follows that there must be (compare Fig. 389) at least two conductors per commutator bar. When the number of conductors is not too great this construction is adopted, and we should then call this a "bar" winding, the winding shown in Fig. 392 being of this type. When, however, the number of conductors on the armature is too great, several turns must be included between each commutator segment. A multiple turn winding, as shown in Fig. 382, page 433, must be adopted; and in this case round wires are generally used, as solid copper strip, except it be of favourable size, gives trouble in winding, and laminated strip, consisting of a number of strips braided together, of the required cross-sectional area is preferred.

In all slotted armatures the bars or multiple turn coils lie, as a necessary consequence of the method of winding adopted, two deep in the slot, the right-hand side of one turn or coil coming from one

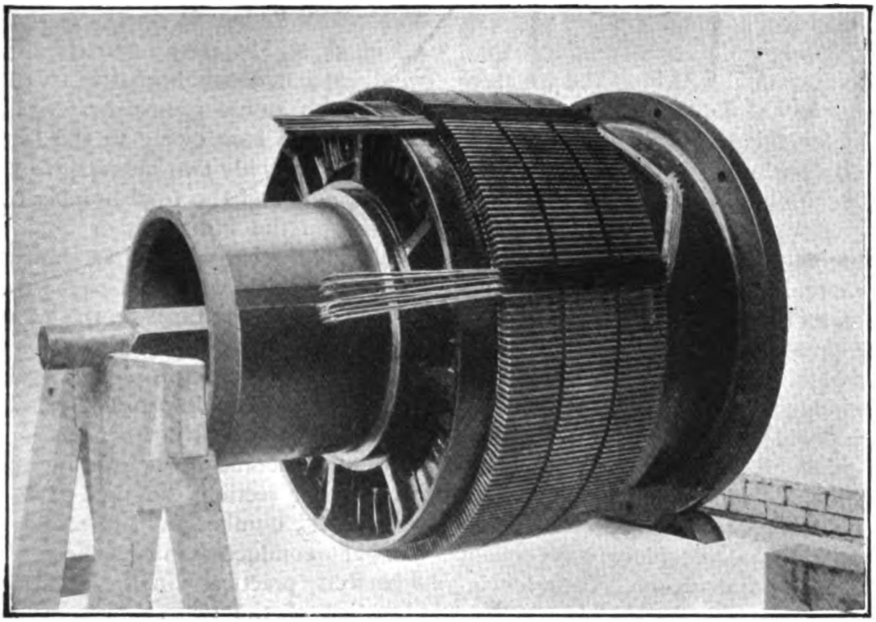


FIG. 392.—COMMENCEMENT OF WINDING OF AN ARMATURE FOR EITHER LAP OR WAVE WINDING.

pole lying above or below the left-hand side of another coil coming from the next pole, and so on. Between the conductors lying in the top and bottom coils of the slot a considerable difference of voltage always exists, owing to the fact that these conductors are brought together from points on the surface of the armature lying under different poles ; and good insulation must therefore be provided between the top and bottom coils.

There will be always as many commutator bars as slots on the armature, or more commonly there are more, three segments per slot being very common, sometimes even as many as five segments per slot being used in small, high voltage armatures where, for reasons of sparkless collection at the commutator, many segments are necessary, and owing to the small size of the armature it is necessary to keep the number of slots as few as possible, in order that the proportion of copper to insulation in the slot may be as great as possible ; for, obviously, if we use many narrow slots, we cannot get in as much total copper, owing to the fact that the necessary thickness of insulation lining the walls of the slot will be the same in each slot, independent of the number of slots used.

Space does not permit us here to give more than an outline of the many different variations of the simple lap and wave windings which may be employed for multipolar machines.

For two-pole machines the simple lap drum winding is universal. Fig. 389, page 437, which shows an imaginary winding for a two-pole machine, will give an idea of the design and operation of such a winding. In this case there are four commutator bars and eight conductors, or four turns of winding. We might consider every two adjacent conductors as being sunk in a slot, which would give four slots in all. An important point to notice is that from one brush to the other there are two paths or circuits through the armature, and that, therefore, the total E.M.F. of the armature is equal to half of that of all the conductors in series for this two-pole case.

The ring winding shown in Fig. 388, page 437, also has two circuits through the armature from brush to brush. If the lap wound armature has four poles, there will be four circuits through the armature; if six poles, six circuits, and so forth.

The wave windings, however, differ in this respect, in that for the ordinary wave windings there are only two circuits through the armature, whatever the number of poles. In the case of both lap and wave windings the number of circuits through the armature can be increased by superimposing two or more independent windings on the armature. Thus, for instance, we can use a "duplex" lap winding on a bipolar dynamo or motor, which will give four circuits, or we can make a four-circuit winding for a six-pole machine by using a "duplex" wave winding.

The lap winding is often called a parallel winding, owing to there being as many parallel circuits through the armature as poles, as distinct from the wave winding, which is similarly known as a "series" winding.

We will illustrate a typical winding in order that the matter may be better understood, taking the case of a four-pole motor of moderate size in which it is found that 576 conductors approximately are necessary for the prescribed design.

From general considerations—the size of the armature and so forth—48 slots are considered about the right number to employ, and there will thus be 12 conductors per slot; and, if we decide to use a commutator with 144 parts, we shall then have three commutator bars per slot and, necessarily, two turns per commutator bar; and if laminated strip be used the conductors will lie best in the slot as shown in A, Fig. 393. This is for a four-circuit or lap winding; but, as an alternative to this, we might wish to use a wave or series winding, in which case, owing to the fact that there will be only two circuits, we should require only half the total number of conductors on the armature, or 288, which would give a bar winding as shown in B, Fig. 393, which will be cheaper to wind owing to the fewer turns on the armature; and also solid copper bars can be easily used in this case, meaning an additional reduction in cost. Unfortunately, however, a *wave* winding will not connect up in a four-pole machine if an even number of commutator sections be used; we must use an odd number, say 143 sections, and thus 286 conductors must suffice. This is a perfectly practical winding, and the employment of the two conductors less can be made up for by a slight alteration in the field winding of the motor or dynamo, as the case may be. Actually 288 conductors would be placed in the armature, but only 286 would be connected up, the remaining turn being left as a dummy coil. In such a four-pole machine, in order to avoid the use of a "dummy coil," an uneven number of slots would have to be employed; but this, while possessing no electrical disadvantage, would not be as convenient to adopt, probably, in the majority of cases, as with most stamping machines it is cheaper to stamp out an even number of slots.

Reference must be made to a standard text book on armature windings for the various formulæ for the different types of winding, which, in connection with the number of poles, give the numbers of conductors which form practical windings; and it is only when these various formulæ have been developed that the whole theory of armature winding can be completely grasped.

We will now proceed to deduce the

elementary relation connecting the speed of the armature, the number of conductors in the armature, the strength of the magnetic field, and the resulting E.M.F. generated in volts. Referring to the ideal simple dynamo with the single loop, as shown in Fig. 368, Chapter I., we have seen that in one revolution of the loop the total flux will be cut twice by each side of the loop and, therefore, with this single turn and a speed of one revolution per second, we should require a flux of $\frac{10^8}{4}$ lines to generate one volt, there being two conductors in series, each cutting the flux twice in the revolution. If we take now a drum winding, such as is shown in Fig. 389, we find, as we have already seen, that from the positive to the negative brush there are *two* circuits through the armature, and we should therefore require in this case $\frac{10^8}{2}$ lines to generate one volt at a speed of one revolution per second for every two conductors or, in other words, for every turn on the armature. The conductors in one circuit being all in series, the voltage in one conductor must be multiplied by the number of conductors in series to give the total voltage between the brushes. We see, then, that owing to the fact that we have two circuits through the armature we can apply this simple rule to estimate the voltage produced by such an armature. Now consider the case of a machine with four poles and such a drum winding. There will now, obviously, be four circuits through the armature (for a parallel or a ring winding), there being, of course, four collecting points, two of these being + and two −, and between any two brushes of opposite polarity there will exist the full voltage of the machine. In the four-pole machine the distribution of the magnetism is as is shown in Fig. 394, the flux from one pole, after passing into the armature, dividing into two paths and flowing as it were right and left through the armature core back to the poles of opposite polarity. The flux from the poles, in passing through the yoke, similarly divides, thus completing the magnetic circuit as shown. In this case the simple rule will again apply as though each conductor cuts the flux from one pole four times during each revolution; yet, as there are only one-fourth the number of turns in series between the positive and negative brushes, the total voltage generated will be the same. We thus see that, for a machine having any number of poles, if there are as many circuits through the armature as poles, we can at once calculate the voltage produced in terms of the flux from one pole, the total number of conductors, and the revolutions per second.

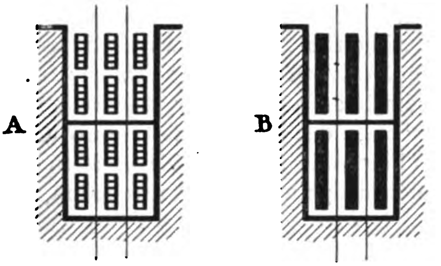


FIG. 393.—CONDUCTORS IN POSITION IN ARMATURE SLOT (SECTION).

In this four-pole case, if a wave winding were used so that there were two instead of four circuits through the armature, we should have obtained, with the same total number of conductors, double the voltage. Conversely, to obtain the same voltage we should only require one-half the total number of conductors. In the case of many poles and only two circuits, we should have to multiply the voltage produced by the number of pairs of poles. In fact, to generalise, we can write :—

$$E = \frac{NZn}{10^8} \times \frac{p}{c}$$

where E = the total electromotive force generated in volts,
N = the total number of magnetic lines per pole,
Z = the total conductors on the armature,
n = the revolutions per second,
p = the number of poles,
c = the number of circuits through the armature.

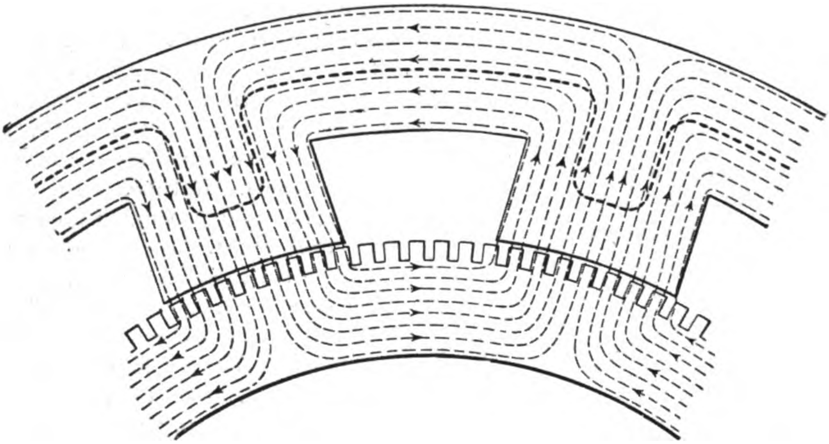


FIG. 394.—DIRECTION OF FLUX IN PARTS OF MULTIPOLAR DYNAMO.

ADVANTAGES AND DISADVANTAGES OF DIFFERENT TYPES OF WINDING.

As we have said, the ring winding is practically obsolete, and it has many grave disadvantages. Firstly, there is more idle copper than is the case with surface-wound armatures, and, secondly, it possesses constructional difficulties, because the turns of the winding have to pass through the inside of the core, and this necessitates expensive hand labour.

Whether any given armature shall be wound as a lap or wave winding depends largely upon circumstances. Sometimes there is no choice, especially in large multipolar dynamos, owing to the fact that for a given size of armature, voltage, and speed, the number of conductors or turns is practically fixed, that is to say, for a given type of winding. In a case such as this, and especially when the dynamo or motor has many poles, we are able to diminish the total number of conductors by using the series or wave windings as compared with the lap or parallel windings inversely as the number of poles, and this may often decide the question as to which winding shall be used. There is one very important point in this connection which must never be lost sight of. We have seen that in the lap or parallel winding there are as many circuits as there are poles, whereas in the simple wave winding there are only two paths through the armature, whatever may be the number of poles. In the series winding there may exist some difference in the strength of the magnetism from the different poles without any detrimental effect, for as these windings zig-zag round the armature many times before the winding is complete, any slight differences in the voltages induced under the different poles cannot result in any appreciable difference of voltage between brushes of the same polarity. In the parallel winding, on the contrary, if there exists any difference in the strength of the field under different poles, we may have appreciable differences of voltage produced between the different brush sets, and as these brush sets of similar polarity are connected together, equalising or circulating currents are produced, which decrease the efficiency of the machine, and may cause injurious sparking at the brushes. This effect is cumulative, for if the commutator, in consequence of the sparking, which is caused by the lack of balance in the circuits, becomes blackened, the magnitude of the circulating currents is increased, causing still more injurious sparking and heating of the armature. When it is necessary to use such windings, the trouble can be got over by the use of equalising connections.

Fig. 395 shows such equalising connections fitted to a large multipolar armature by the British Thomson-Houston Co., Ltd., of Rugby. Seven short circuiting rings are arranged at the back of the armature, and tappings are taken from equipotential points in the armature windings.

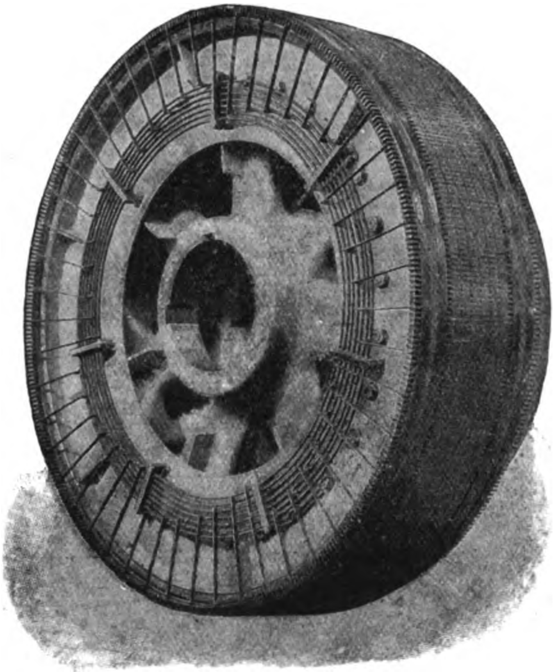


FIG. 395.—EQUALISING CONNECTIONS IN A MULTIPOLAR ARMATURE.

COMMUTATION.

That a dynamo or motor shall run at its full load without any noticeable or harmful sparking at the brushes is of the very greatest importance; in fact, however perfect the machine may be in other ways, should it fail in this respect, it must be at once condemned as unsatisfactory.

Not only must there be no sparking at the commutator when the machine is loaded, but it should not be necessary to move the brushes round the commutator as the load varies; in other words, it must fulfil the requirements of a fixed brush position. All modern specifications demand that there shall be no shifting of the brushes from no-load to full-load, and *vice versâ*, and this is absolutely necessary in the case of the great majority of motors, for often motors are subjected to rapid variations in load, and are in positions so inaccessible that no attention whatever can be given to the machine when running. In some cases a little shifting of the brushes is permissible with large dynamos, but modern practice generally makes the same stipulation even for the largest machines.

Sparking at the brushes will soon ruin the best machine if the trouble is not arrested in its infancy, for even slight sparking, if allowed to go on, soon blackens the commutator. The trouble then increasing, the commutator and brushes run very hot, and the commutator becomes pitted and rough; in fact, the effect is cumulative, and especially with the parallel windings is this noticeable.

Designers have naturally given great attention to the question of commutation, and as a result it is possible by careful consideration of the principles involved, and by taking advantage of a few simple rules, to say from the constants of any particular design, whether the commutation will be quite satisfactory or not. As in all other questions connected with design, good judgment and experience are of course necessary to make the closest predictions; but very little experience is, however, necessary to determine whether a given design is quite safe as regards commutation, or whether it is very doubtful that the machine will run sparklessly.

Some years ago very arbitrary rules were in use, and the actual experience of designers with particular types was the only safe guide; but now, owing to the better understanding of the actions which go on in the armature, and the classical experiments of Messrs. Parshall and Hobart and others, rules of thumb have given place to infinitely more reliable methods.

We have seen that the function of the commutator and brushes is to reverse the connections of the rotating armature coils in relation to the fixed brushes in order that the alternating currents induced in the armature may become unidirectional in the external circuit.

We will consider more closely what happens *under the brush* when this change in connections is effected, bearing in mind that, by passing a brush, a coil is transferred from what is electrically one operative portion of the armature to the next; in a bipolar machine, from one half to the other. This transference necessarily involves reversal of the current.

Take the case of the simple ring winding as shown in Fig. 396. This shows diagrammatically a bipolar machine with eight sections in the commutator, and between adjacent segments there are included two turns of armature winding. The directions of the induced currents in the winding will be as shown by the arrows, the collecting brushes being placed at top and bottom across a diameter.

Considering the top brush, the currents from the right and left sides of the winding will flow up (or down, of course, if the rotation of the armature be in the opposite direction), and at the moment when two segments are short circuited by the brush, the currents from the two halves of the winding will be flowing down adjacent commutator lugs, and away through the brush, while the coil B will be short circuited. When the coil arrives at the position C it will be carrying the full current, but in the opposite direction, and so the process will go on as long as the armature revolves and delivers current to the external circuit.

Now the whole matter of sparkless commutation depends upon what takes place in the short-circuited coil during this period. Immediately before the instant of short circuit the coil* is carrying the full current of that portion of the armature and the moment it emerges from the short-circuited condition it has to carry the same magnitude of current, but in the *reverse* direction. This reversal of necessity sets up an E.M.F., the E.M.F. of self induction opposing the change, and this E.M.F. will occasion a spark at the brush tip as the trailing segment of the coil under consideration passes on from beneath the brush. The only way to stop the sparking is by the introduction of aids to the reversal of the current during the period of short circuit so arranged that they shall produce in the coil a reversed current of the same magnitude as it will have to carry when it emerges from under the brush. The aids introduced are of two kinds, resistance and E.M.F. Until of more recent years, the practice was to use reversing E.M.F.s principally, but latterly carbon brushes have become universal, and by reason of their resistance have largely contributed to the successful accomplishment of sparkless commutation. If no other E.M.F. were introduced the current in the short-circuited coil would die down, by reason of resistance of the path in which it was circulating, at a rate depending on the number of linkages of magnetic lines and the magnitude of the resistance. The greater the number of linkages the greater the energy stored (*see* page 200), and the greater the resistance the better the dissipation of the energy. It would therefore be possible to cut the current down to zero during the short-circuit period by brush contact resistance alone, but this would not mean sparkless running, because the coil would, on leaving the brush, be subject to a sudden change in leaving immediately to carry the current of the armature portion into which it here enters electrically. It is not therefore sufficient to destroy the current formerly flowing, but it is necessary to generate a reversed current of equal magnitude so that there shall be no sudden change in the coil at the instant when it leaves the brush and becomes electrically part of the adjacent operative portion of the armature. The generation of such a current during the period of short circuit is effected by the introduction of an E.M.F. of similar sign to that existing in the adjacent forward armature portion, the E.M.F. being set up by the presence of a magnetic flux of appropriate sign and magnitude. This flux is to be found in the fringing of the field from the pole beneath which the coil is about to pass, and the fringe is often called a commutating fringe for that reason.

---

* It is immaterial whether the conductors connecting one commutator segment with the next constitute what may clearly be seen to be a coil or whether they are merely two bars of a winding; all that is said here of a "coil" will apply to any such case.

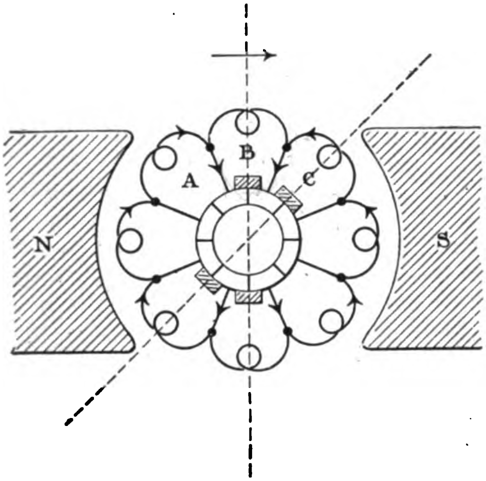


FIG. 390.—COMMUTATING AXES SHOWING ANGLE OF LEAD.

Now it is evident that this process of short circuiting a coil carrying a considerable current, reducing this current to zero, and sending an equal current in the opposite direction in the coil, must be accomplished in a very short time (in most cases less than the hundredth part of a second), depending upon the speed of the commutator, the number of segments in the commutator, and the number of segments covered by the brush.

The length of time which must be allowed in order that the current may die down, will depend upon the self-induction of the circuit and the magnitude of the current flowing. The self-induction of any coil of wire is a function of the number of turns in the circuit and the nature of the surrounding medium, and the greater the self-induction and the current, the larger the spark will be when the circuit is suddenly broken. Thus a solenoid of a given number of turns carrying a given current will exhibit a much larger spark if an iron core is inserted in the coil than when the connection is broken without the core, the self induction having been increased by the presence of the iron which, by reducing the reluctance of the magnetic path, causes more magnetic lines to be linked with the coil. Hence, when the circuit is broken, more energy is available for the production of the spark.

An armature coil, when short circuited by the brush during the process of commutation, will similarly tend to cause more sparking if its self-induction be increased, the current in the short-circuited coil remaining the same ; or if the current is greater, obviously the tendency to spark increases.

Now, therefore, in order to ensure sparkless running, there are three quantities, the value of which should receive the greatest attention : first, the time of commutation should be as long as possible ; secondly, the self-induction of the coil should be as low as possible ; and, thirdly, the current in the coil should be as small as possible.

Consider a dynamo or motor intended to run at a certain speed and to give a certain output in amperes and volts, and let us see then how the sparking constants of the machine could be made as good as possible. We should first, from the number of poles and the dimensions of the field system, determine the necessary number of conductors on the armature, and we should then have to decide upon the number of commutator sections. If the armature required a large number of conductors we should probably have to use several turns of winding per segment, as otherwise the number of sections would be prohibitive, but if the armature had few turns we could probably use a "bar" winding, using only a single turn between two commutator bars. It is an obvious conclusion from what we have said above that the larger the number of segments, or the fewer the turns of winding included between each segment, the better the commutation will be, for other things being equal, the fewer the turns the less will be the self-induction of the coil undergoing commutation.

As the result of experiments first made by Messrs. Parshall and Hobart on the self-induction of armature coils embedded in slots under different conditions, it is possible to calculate roughly—and though rough, the calculation is of great service—the value of the *reactance voltage* in the coil or coils undergoing commutation. This reactance voltage is the E.M.F. of self-induction set up in the short-circuited coil, the current in which has to die down to zero and build itself up in the reverse direction in the short period during which the brush short-circuits the coil.

The reactance voltage is $2 \pi n$ L C,* where n is the frequency of reversal of the current in the coil ; L is the coefficient of self-induction of the coil in henrys, and C the current in amperes. All these quantities are readily determinable with the exception of the value of L, the exact value of which can only be ascertained satisfactorily by practical experiment in any particular case ; but such experiments have shown that it is possible to take an average value, which, if used with some caution, enables an approximate and relative value of the reactance voltage to be obtained, which is of great service.

In order to obtain a general formula for the calculation of the reactance voltage applicable at once to any design, it has been usual to neglect the self-induction of the "end windings" of the armature, and consider only the "embedded" length of conductor. This is not strictly correct, but in the majority of designs the self-induction of the embedded portion of the winding is certainly very much greater than that of the "free" length.

It has been found that for the length of the coil embedded in the slots there will be set up about 10 C.G.S. lines per ampere per inch of embedded length.

---

* *See* page 358.

Various formulæ, in which all the necessary factors for the calculation of the reactance voltage appear, have been given, a convenient form being the following :—

Reactance voltage =

$$\frac{m \times t^2 \times p \times \mathrm{C} \times rpm \times d \times l \times k \times \cdot 33}{c \times b \times 10^8}$$

where :—

m = the number of segments covered by the brush.

t = the number of turns of winding between each two segments.

p = the number of poles of the machine.

C = the current per circuit of the winding in amperes.

rpm = revolutions per minute of the armature.

d = diameter of the commutator in inches.

l = the embedded length of the armature coil, that is, the iron length of the armature in inches.

k = lines per ampere per inch, = 10 usually.

c = the number of circuits through the armature.

b = the width of the brush in inches.

We have not space here to deduce this rather lengthy formula from elementary considerations, but, as the various factors are all separated out, it is a very instructive form, and an example of the calculation of the reactance voltage will be given in Chapter III. Reference should be made to a standard text-book, such as Hobart's "Electric Motors," for a fuller explanation of such formulæ. The permissible value of the reactance voltage which is compatible with sparkless running will depend upon the means employed to counteract its effect, and it must be approximately counteracted if the machine is to run sparklessly. There are three ways in which the reactance voltage can be compensated for, firstly, by the use of carbon brushes, without having recourse to the commutating fringe of the machine itself (which, as we shall presently see, has been the most usual method); secondly, by the use of the "commutating fringe," a name given to the fringe of magnetic lines which spreads out from the pole tip and provides an E.M.F. in a coil before it has come into the range of the full field of a pole; and lastly by the use of auxiliary or commutating poles. Roughly we may say that the carbon brushes alone, without other means, can deal with one to two volts reactance, while with carbon brushes, and the assistance afforded by the commutating fringe, up to four volts can be dealt with, while with auxiliary poles we can go to twelve volts, or even much higher.

Referring to Fig. 396, we have shown the two brushes placed midway between the pole tips, or, as it is called, in the "neutral" position, and, as we have seen, the reactance voltage must necessarily be very low if the brushes are to be placed in this position; but it is sometimes necessary, especially in the case of motors, that the machine shall be able to run in either direction without movement of the brushes, and in this case the brushes must be placed in the neutral position. By the term "neutral position," we mean here and throughout the discussion the geometrical neutral position as indicating the position of the brushes when they are placed midway between the poles or the equivalent position on the commutator, depending upon how the armature connections are taken out to the commutator. Copper brushes would be useless for this purpose, as even the small permissible reactance necessary under these conditions would cause injurious sparking with metal brushes; but carbon brushes act in a very convenient way, in that when the current is flowing through them there is a considerable drop of voltage across the contact between the carbon block and the commutator face, which really acts as if the brush were able to set up a back E.M.F. The value of this apparent back E.M.F. is usually about one volt under each brush, thus enabling reactance voltages of this order of magnitude to be compensated for by the brushes alone.

The contact resistance of copper brushes is only about $\frac{1}{10}$ that of the ordinary carbon brush, and it will be obvious therefore that if copper brushes are to work satisfactorily some other means must be employed to compensate the reactance voltage; and in the early days when such brushes were universally used, fringe commutation was always resorted to, and in the ordinary modern dynamo or motor, unless there be some special conditions such as reversibility, speed, or voltage variation, such is also the case.

The approximate position for the brushes when fringe commutation is resorted to is shown by the dotted axes in Fig. 396, the brushes being moved to the right or left, according to the direction of rotation, and whether the machine is running as dynamo or motor.

The object of moving the brushes is to ensure that while the current in any particular coil is being reversed that coil shall at the same time be cutting through a weak magnetic field under the pole tips, just sufficient to induce a small voltage equal to the reactance voltage, which is thus compensated for.

A little consideration will show, however, that if we shift the brushes to this position, so that sparkless commutation is obtained at full load, then at no load when no appreciable current is flowing through the armature, we shall still have the magnetic field acting upon each coil as it is commutated, but no reactance voltage in the coils, and therefore the machine will tend to spark at no-load. With copper brushes it is practically always found necessary to move the brushes as the load varies in order to obtain, by moving the coils under commutation into a weaker or stronger field, just sufficient counter E.M.F. to cancel the reactance voltage. With carbon brushes and a well-designed machine, it is possible to place the brushes in a position intermediate between the exact no-load and full-load positions, reliance being placed on the help afforded by the contact resistance of the carbon brush, and thus obtain a fixed brush position. This *fixed* brush position must not be confused with the *neutral* position, as when the brushes are in the neutral position no help at all is afforded by the magnetic fringe from the poles, entire reliance being placed on the contact resistance of the brush, while with the fixed brush position very considerable assistance is given by the commutating fringe, though, as we have seen, the peculiar properties of the carbon brush are also in operation.

In order to obtain a sufficiently strong commutating fringe it is necessary to make the air gap long so that the ampere turns spent in driving the flux across the air gap shall bear a sufficiently high ratio to the ampere turns on the armature, and we shall look more closely into this when we come to consider the reaction of the armature ampere turns upon the field. Up to the present, we have not mentioned this, as in order thoroughly to understand the theory of commutation, it is necessary to distinguish sharply between the influence of reactance voltage on the commutating properties of any machine in contradistinction to the effect of the field distortion produced by the currents flowing in the armature.

The auxiliary or commutating poles to which reference has been made provide an entirely distinct commutating field, and enable much higher reactances to be dealt with, owing to the fact that the strength of the commutating field provided by the auxiliary poles increases with the load, which is not the case to any extent when a portion of the magnetism of the main field is relied upon.

With commutating poles the brushes are placed in the neutral position, and the machine is thus perfectly reversible, and much higher reactance voltages can be compensated for by this means, allowing in all cases much greater elasticity in the design; in the next chapter we shall illustrate the application of these auxiliary poles in the analysis of an actual design.

We must now consider the influence of the armature field on the main field, or the *reaction* of the armature, which is an effect of great importance.

When no current is flowing through the armature, the main field will be undistorted as in Fig. 397, but when currents are flowing in the armature winding the flux will be *skewed* round by the action of the armature field as shown in Fig. 398, and this effect will be increased if the brushes are not placed in the neutral position, but are given the "lead" which, as we have seen, is necessary if advantage is taken of the magnetic fringe from the poles to assist the process of commutation. The cause of this distortion will be understood by reference to Figs. 399 and 400, the armature conductors being divided into two sets in each case by the dotted line *x y*. This line indicates the position in which the brushes are placed on the commutator relative to the armature, in the first case in the neutral position (Fig. 399), and in the second case (Fig. 400) when a "lead" is given, and if we now consider the currents flowing in the conductors on the armature between the planes *a a*, and *b b*, it will be at once seen that the currents flowing through these conductors set up a magnetic field directly opposed to the main field produced by the field magnets, and this field would tend to exercise a direct *demagnetising* effect on the main field, leading to an actual diminution of the main flux, while the field produced by the remaining conductors under the poles produces a *cross magnetising* effect which tends to distort the main field.

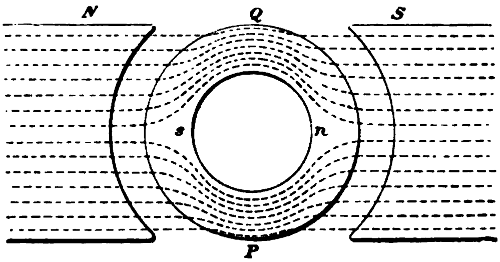


FIG. 397.—UNDISTORTED FLUX IN BIPOLAR MACHINE.

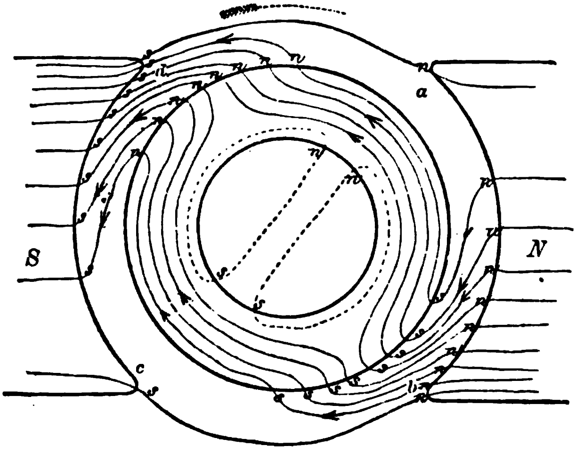


FIG. 398.—TWISTED FIELD DUE TO MAGNETIC REACTION OF ARMATURE.

Now there are two very important considerations to remember here, the first being that if the brushes are placed in the neutral position, that is, the position indicated in Fig. 399, there will be no true demagnetising effect, for in this case the four top and bottom conductors shown between the planes *a a*, and *b b*, would not all be carrying current in the same direction (which is the case if the brushes are given a lead), but the two left-hand conductors would be carrying currents in one direction and the two right-hand conductors currents in the opposite direction, and the effects would then cancel each other ; but, in stating this, we must be careful to point out that the cross-magnetising field is still acting, whether the brushes be in the neutral position or not, and there will still be the same tendency for the flux to be distorted. In the two-pole machine the value of the armature demagnetisation will evidently be obtained by multiplying the total number of turns thus acting between the planes, $a\,a_{\prime}$ and $b\,b_{\prime}$, by the current flowing in each, or, in other words, by multiplying half the number of conductors thus reckoned by the current per circuit in the armature. In the case of a machine with more than two poles, the exact calculation of the demagnetisation is a more complex matter, but we must always remember that the amount of the demagnetising effect depends entirely upon the position of the brushes.

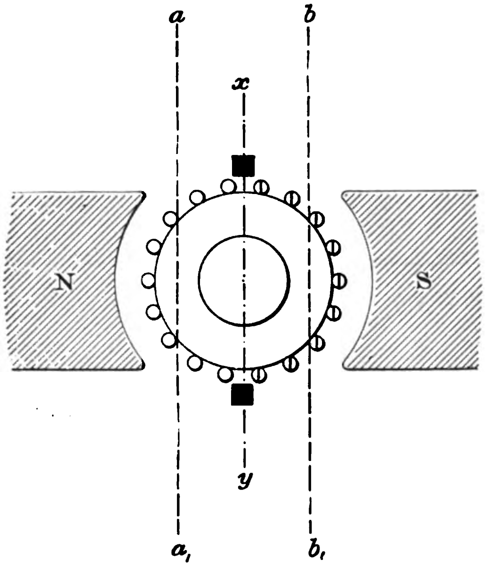


FIG. 399. — DISTORTING EFFECT OF AN ARMATURE CURRENT WITH BRUSHES IN NEUTRAL POSITION.

We have now seen that the field is distorted by the action of the cross-magnetising ampere turns on the armature, and we have also seen, when discussing the methods adopted for compensating for the reactance voltage, that it was necessary to move the brushes from the neutral position in order to take advantage of the magnetic fringe to effect commutation. Now in the case of a dynamo a little consideration will show that the field, will be distorted in the direction of the rotation, and therefore, on account of the action of the cross-magnetising field it is necessary to move the brushes still further forward to " catch up," as it were, with the commutating fringe, and as the amount by which the flux will be distorted will depend upon the magnitude of the currents flowing in the armature—in other words, upon the

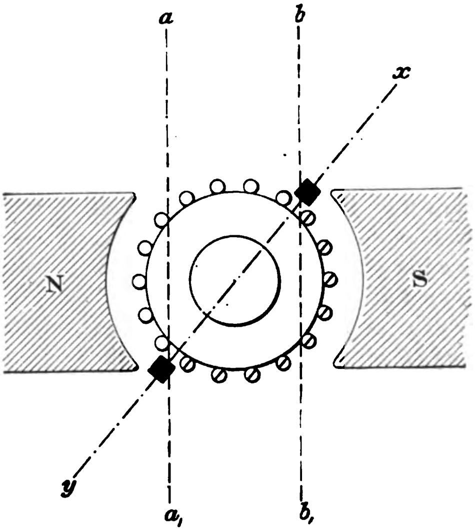


FIG. 400.—SEPARATION OF DISTORTING AND DEMAGNETISING EFFECTS WITH LEAD ON BRUSHES.

load—it is obvious, therefore, that from this cause also it should be necessary to shift the brushes between no load and full load; in fact, the effect of the cross-magnetising action of the armature tends to render brush shifting necessary, exactly as it is necessary to move the brushes in order to get into the proper strength of commutating fringe to neutralise the effect of the varying reactance voltage.

In the case of a motor, the field is shifted backwards and not forwards; and, hence, motors must be given a *backward lead*, the opposite being the case with dynamos, which must have a *forward lead* in respect to the direction of rotation.

We have already mentioned that, if a motor is to be reversible, the brushes must be placed in the neutral position, but for dynamos this is rarely necessary owing to there being no necessity to reverse the rotation; but a fixed brush position is necessary, and this fixed brush position must in nowise be confused, as we have mentioned, with the geometrical neutral position or "neutral" position as we have used the term here. Some writers have used the term neutral position to define the place at which the brushes are set for sparkless commutation when a lead is given, either backward or forward as the case may be; but as this position may vary with the load (when no fixed position can be given to the brushes), it seems best to use the term neutral in a space sense as defining the position midway between the pole tips.

A glance at Fig. 401 will make this question of brush position quite clear. For a given machine for a given direction of rotation there will be no less than seven principal brush positions, depending upon whether the machine is used as a dynamo or motor. Firstly, the neutral position, which will be the same for the dynamo or motor case; then the backward and forward fixed brush positions for motor and dynamo; and, if the lead be not fixed, the no-load and full-load positions in each case.

We have stated approximately the magnitude of the reactance voltage which can be permitted when the brushes are placed in the neutral position, and shown how essential is the employment of the carbon brush in this connection, and how, for the fixed position of backward or forward lead, success can only be ensured by their use, copper brushes, owing to their low contact resistance, being permissible only in those cases when brush shifting with variations of load is possible; but due attention must always be given to the magnitude of the armature reaction, for if the armature is too heavily loaded, a fixed position may not be possible even with a low reactance voltage.

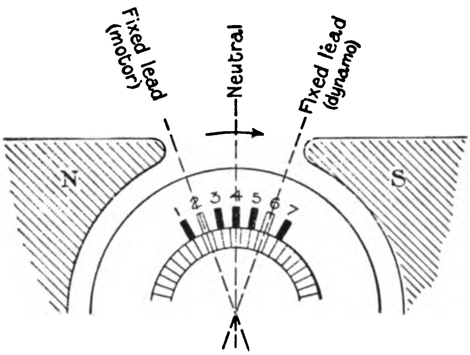


FIG. 401.—BRUSH POSITIONS FOR VARIOUS DUTIES.

The armature ampere turns lying just under the poles are, as we have seen, those which produce the cross magnetising field and cause the distortion of the field flux. The amount of the distortion depends upon the ratio of the field and armature ampere turns; the stronger the field the less the distortion, and *vice versâ*. The best way to resist the distorting effect is to saturate the armature teeth, and it is the universal practice to run the teeth at high densities, the common value ranging from 130,000 to 150,000 lines per square inch at the roots of the teeth. It is not well to go beyond this, as even at the lower figure all the flux will not go through the teeth, but some will leak and pass down the sides of the slot, and eddy currents may in this way be induced in the armature conductors, especially if a bar winding is used, owing to the large size of the conductors. The teeth being well saturated, the flux at the pole face is able better to resist distortion, as the shifting of the flux will tend to reduce the saturation at one pole tip and increase it at the other; in fact, saturating the teeth acts as though it stiffened the field.

In order that a fixed brush position with reasonable reactance voltages shall be ensured, the field ampere turns per pole spent in driving the flux through the air gap and teeth should be about 50 per cent. greater than the armature ampere turns under the pole.

It is important also for the fixed brush position that the ratio of pole arc to pole pitch should not be too small; for, if this be the case, the actual distance (or angle round the commutator) between the best no-load and full-load positions will be greater, and the mean between these, the fixed brush position, will not be so easily attained.

Carbon brushes are nowadays employed on all standard machines, but copper brushes still have a limited application for certain purposes. They are used for extra high speed machines, most of the present direct current turbo-dynamos employing some form of copper brush, and some further mention of this application of copper brushes will be made in the description of such machines in Chapter III.

For very low voltage dynamos, yielding very heavy currents at a few volts, for plating or general electro-chemical work, copper brushes are necessarily employed because of the very large commutator which would be required to collect the current, and also on account of the lowering in efficiency which would result owing to the large contact resistance of carbon brushes as compared with copper.

HEATING.

Having now dealt with commutation, which is one of the principal factors that limits the output which can be obtained from a given machine carcase, we will now briefly consider how the heating of the armature, commutator, and field coils of a dynamo puts similar limits upon the output. A limit is set to the permissible temperature rise in a dynamo or motor by the fact that the materials which are used to insulate the copper conductors in the slots and other parts are necessarily materials which cannot stand a high temperature, such as the cotton covering, tape or cotton braiding, on the armature and field windings and the paper or insulating cloth, etc., which is used to insulate the winding from the armature core. The mechanical construction of the machine also requires that the heating be not excessive, otherwise injurious strains due to metallic expansion and contraction may be set up. Further, the pressure regulation of the machine may suffer if the temperature attained is excessive, owing to the increase in electrical resistance of copper with temperature. Modern practice demands that the temperature *rise*, under continuous running conditions, should not exceed about 70°–80° F., and this means that under a severe overload the temperature rise may be as high as 90°–100° F. above the surrounding atmosphere. Anything much beyond this is certainly inadvisable so long as the present insulating materials are employed. The heating of the armature is, of course, the result of the losses taking place in the

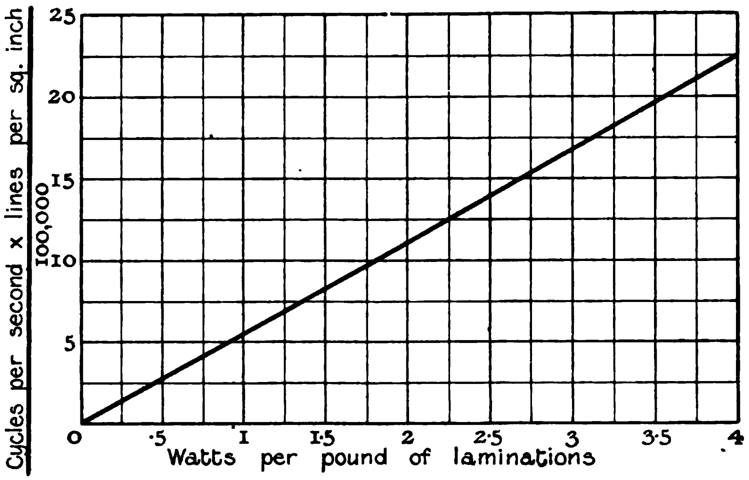


FIG. 402.—IRON LOSSES IN LAMINATED IRON FOR ARMATURE CORES.

windings (the copper loss) and the iron or core losses (the sum of the eddy and hysteresis losses). It has already been shown in Section V. that the loss in watts in any copper conductor is obtained by multiplying the resistance of the conductor in ohms by the square of the current in amperes flowing through it. As it is an easy matter to calculate the resistance of the armature from the size and length of the conductors, we can at once, knowing the current flowing through the armature, calculate the watts lost in the copper. Similarly, knowing the thickness, quality, and weight of the laminations composing the core, the density of the magnetic flux, and the frequency, as determined by the speed and number of poles of the machine, we can calculate the iron loss in watts in a similar manner to the calculation of the iron losses in transformers, as has been shown in Chapter V., Section VI. For practical calculation the curve given in Fig. 402, which gives the actual loss for the ordinary quality of iron which is usually employed, can be used. This curve takes into account both the hysteresis and eddy current losses. The actual losses taking place in the core vary considerably according to the method of building up in the shops; the slots are often filed or milled out to get a smooth surface on the sides of the slot after the core has been assembled, and this process certainly increases the losses owing to local eddy currents through the burred edges. The tested losses vary greatly, and considerable margin must be allowed in the heating calculation for a possible increase on the loss over that anticipated, unless tests are at hand on armatures built of the same iron with and of the same general proportions. The curve given is due to Mr. Hobart, and expresses the average result obtained on 25 machines of different sizes and speeds. The thickness of the armature iron used was 13 mils., but if thicker plates are used or the slots milled or bad mechanical design adopted (so that eddy currents may take place in armature end plates or shaft or clamping bolts), an increase over the losses indicated by the curve must be anticipated. The temperature rise on the armature depends upon the total number of watts lost in the copper and iron in relation to the exposed surface and the general fanning action, and it is obviously desirable to make the armature as well ventilated as possible in order to utilise to the maximum a given weight of copper and iron. In order to obtain a current of air through the armature to carry away the heat sufficiently rapidly, it is found necessary to provide ventilating spaces through the body of the armature so that the air can be thrown out centrifugally. Fig. 403 shows a large armature with four ventilating ducts through the core, by Messrs. Dick, Kerr & Co., Ltd. This illustration clearly shows how the air entering the interior of the armature can escape through to the armature face, and when running at a good speed there will be a constant tendency for the air to rush out through the ducts by the centrifugal forces brought to play on the air pocketed inside the armature.

Considerable experience is necessary in order to estimate the temperature rise which will be attained by an armature, but a fair approximation can be obtained by the use of the curve in Fig. 404. This curve connects the peripheral speed of the armature (in feet per minute) with the temperature rise which will be attained per

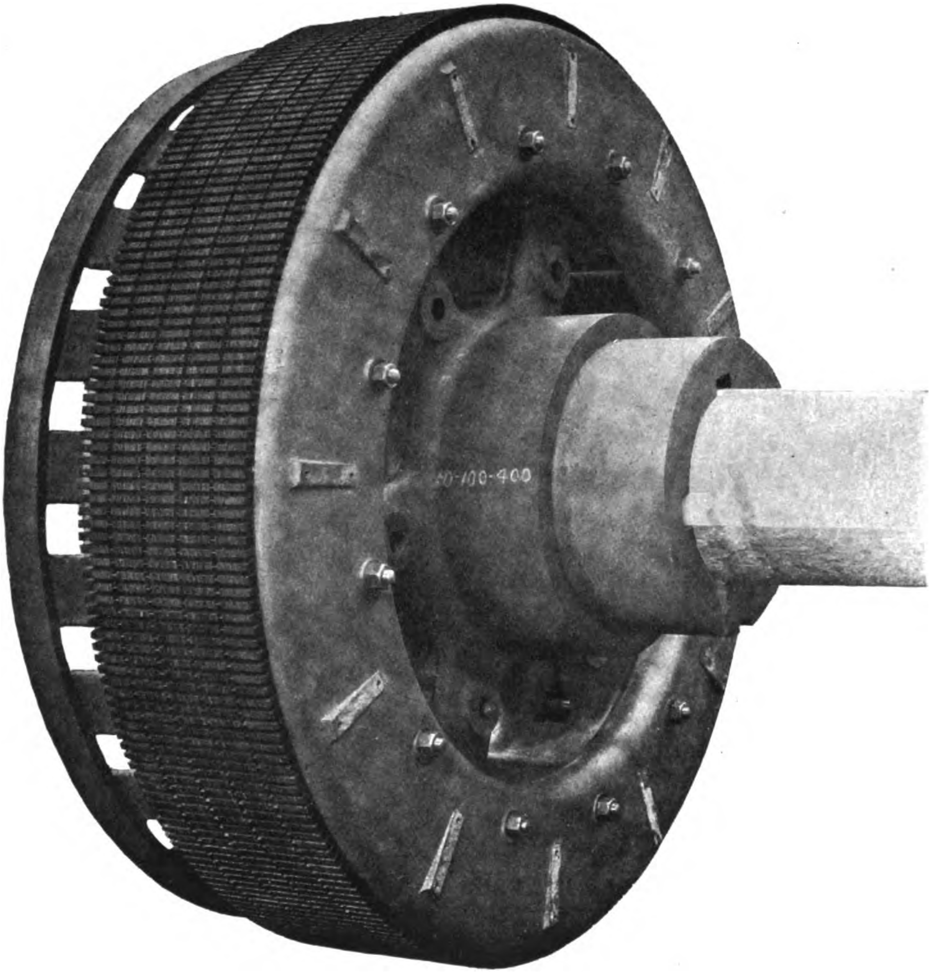


FIG. 403.—UNWOUND ARMATURE FOR MULTIPOLAR MACHINE SHOWING VENTILATING DUCTS.

watt which it is necessary to dissipate per square inch of radiating surface when running continuously. It is, of course, obvious that the greater the surface speed of the armature, the greater will be the general fanning action, and hence the lower the temperature rise for a given dissipation of energy per unit area.

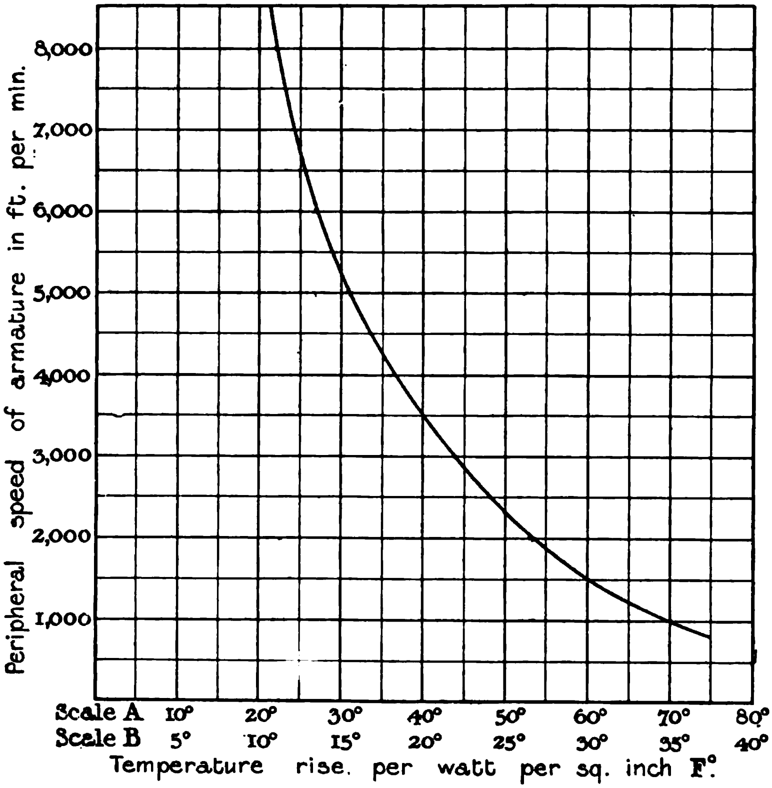


FIG. 404.—CURVES SHOWING EFFECT OF SPEED ON TEMPERATURE RISE IN ARMATURE.

There are two scales of temperature rise, corresponding to large and small armatures, and the method of estimating the radiating surfaces differs for these two classes of armatures. Scale A is for the large armatures, and scale B for the small. It is quite reasonable to adopt a different method of estimation for the large as compared with the small armatures, as will be seen from the following considerations: In the small armatures, the outside peripheral surface only of the armature is really effective in the dissipation of heat; there may be one or two ducts through the core, but these do not help much in getting rid of the heat, and for such armatures up to about 12 inches in diameter the scale B will be used, the watts per square inch being obtained by taking the sum of the whole copper and iron losses and dividing these into the whole peripheral surface of the armature, or

$$\text{Watts per square in.} = \frac{W_{Cu} + W_{Fe}}{\pi d l}$$

where W_{Cu} are the total copper watts, W_{Fe} the total iron watts, d the diameter of the armature in inches, and l the length over the end windings in inches.

For the large armatures, where there is free access of air to the interior of the armature core and effective ducts, we must take account of all such surfaces and use scale A. Referring to Fig. 403, the question arises: Can we simply consider the losses in the armature core and in the copper in the slots only, or the embedded lengths of the windings? Actual tests show that, as a rule, the end windings on large armatures usually run cooler than the iron core owing to the excellent ventilation that the free portions of the windings are subjected to, and it is therefore quite rational to adopt this method. We will, therefore, in this case, consider only the sum of the total iron losses plus the copper loss in the embedded length of the winding in relation to the radiating surface.

For the radiating surface we take the outside peripheral surface of the core, the inside surface of the cylindrical core, and we must add to these surfaces the area of the end plates of the core, for these obviously are effective in getting rid of heat. As regards the ducts it is found that too much surface must not be allowed, and it is therefore best to consider each duct at one surface, that is, only to take one wall of each duct.

Summing up the expression for the watts per square inch in this case will be to a sufficient degree of accuracy:

Watts per sq. in. =

$$\frac{We_{Cu} + W_{Fe}}{\pi d l + \pi d' l + \{(\pi d'' \times r) \times (D + 2)\}}$$

where We_{Cu} = watts lost in the embedded winding,
W_{Fe} = total iron watts,
d = outside diam. of armature,
d' = inside diam. of armature,
d'' = mean diam. of armature core,
r = the radial depth of the core,
D = the number of ducts through the core,
l = the length of core parallel to shaft.

COMMUTATOR HEATING.

The heating on the commutator is due to two causes: (1) The mechanical loss due to the friction of the carbon brushes on the commutator face; (2) the C^2R loss principally taking place at the contact between the brush and the surface of the commutator. To calculate the friction loss we must know the pressure of the brushes on the commutator, the coefficient of friction between carbon and copper, and the surface speed of the commutator. The brush pressure will usually be about one pound per square inch. The coefficient of friction is about ·3 for carbon brushes or about ·2 for copper brushes. Adopting these values we obtain a general formula for the commutator friction as follows:

Friction loss in watts =

$$\frac{S \times A \times d \times r.p.m. \times 2}{10^3}$$

where S is the number of brush spindles, A the contact area of the brushes on one spindle, and d the diameter of the commutator in inches.

In calculating the C^2R loss we assume that all the loss takes place at the brush contact. We have already mentioned that there is a drop of voltage at the contact of the carbon brush with the commutator face of about one volt for the usual current densities employed, namely, about 30 amperes per square inch. If we, therefore, take the total current of the machine and multiply by 2, we obtain roughly the C^2R loss at the commutator. For very soft carbons the loss will be less than this for the same current density; for example, the contact resistance of the X quality brushes of the Le Carbone manufacture is only about ·02 ohms per square inch, and the voltage drop at each brush, at

30 amperes per square inch, will therefore only be 0·6 volts.

Having obtained the sum of the friction and C^2R losses at the commutator, if we express this as a function of the radiating surface in square inches, it will be found that, with commutators at the usual speeds and of usual designs, the temperature rise will be about 20° F. per watt per square inch.

FIELD HEATING.

The field coils on the dynamo or motor are of course designed to provide the necessary ampere turns to maintain the magnetism of the machine at its proper value, as explained in Chapter I. The amount of copper wire which must be used to effect this depends upon the degree of the saturation in the yoke, poles, and armature teeth of the machine. Generally the larger proportion of the copper, however, is necessary to force the flux across the air gap between the poles and the armature. After having decided upon the excitation requisite, the next point is to fix the current density which can be employed in the coils without excessive heating. Knowing the resistance of the coils and the current in them, the C^2R loss can be calculated in the usual way. The temperature which the field coils will attain obviously depends, as in the case of the armature and commutator, upon the exposed surface in relation to the watts lost, expressed as the watts lost per square inch. In practice, however, it is found quite as useful, in many cases, to estimate the temperature rise from the current density in the winding by comparison with tests of other machines. The permissible current densities for ordinary ventilation range from about 1,700 per square inch, in the very smallest machines, to 800 per square inch for very large field coils for slow speed machines. For the great majority of machines the current density ranges from 950 to 1,100 amperes per square inch.

For the field coils of a large dynamo receiving good ventilation from the armature, if we take the total exposed surfaces of the coils, the watts per square inch for a temperature rise of 60–70° F., running continuously, will be about 0·3, this corresponding generally to about 950 amperes per square inch in the copper.

CHAPTER III.—DESCRIPTION AND PERFORMANCE OF CONTINUOUS CURRENT DYNAMOS AND MOTORS.

CHARACTERISTIC CURVES—SERIES MACHINE—SHUNT MACHINE—COMPOUND MACHINE—THE OUTPUT COEFFICIENT—ELECTROLYTIC DYNAMOS—HOMOPOLAR DYNAMOS—SHUNT REGULATION FOR DYNAMOS—MODERN CONTINUOUS CURRENT MOTORS—CRANE AND TRACTION MOTORS.

In the preceding chapter we have given some insight into the design of continuous current machinery, and in the present chapter we shall illustrate the principles set forth by the analysis of some actual examples of modern dynamos and motors, and describe machines of the various types by a number of well known manufacturers.

It is first, however, necessary here to consider more closely how the performance of a dynamo or motor is influenced by the kind of field winding adopted, the demands of practice in general strongly favouring in a particular case one type of winding.

We have explained how a dynamo or motor may be wound as a shunt, compound, or series machine according to the purpose for which it is to be used, and we have made some mention of the action of the three different kinds of winding; but it will be well here to consider the matter at greater length before describing actual machines.

For dynamos the shunt and compound windings are most frequently employed, the series winding being only suitable for arc-lighting dynamos, and nowadays even for this purpose shunt-wound machines are very common.

For traction work, however, compound windings are always used, as, otherwise, the pressure could not be kept up under the constant and sudden fluctuations of a traction load, and as many stations now supply power for both lighting and traction purposes, it has become the almost universal practice to employ generators having independent shunt and series windings, so that the same machine can be run either shunt or compound. Traction generators are generally "over-compounded," *i.e.* the excitation provided by the series winding as the load comes on is more than sufficient to keep the pressure constant, and actually causes the voltage to rise, thus compensating both for the drop in the traction "feeders" and also for the slowing down which occurs even with the best governed engine when a heavy load is suddenly applied.

The series dynamo cannot excite itself until the main circuit is closed, and the fact that the voltage variation is enormous with any change in the load, especially, as we have seen, when the field is unsaturated, renders it quite unsuitable for ordinary lighting or power purposes. In the particular case of arc lighting, however, the series dynamo has been successfully used, as in the case of lighting a number of arc lamps in *series* the main circuit will be always closed and the current practically constant, and it has been found possible with this constant current arc lighting system to regulate the generator voltage very perfectly (by brush shifting or other means), in case some of the lamps are turned off. Such series arc lighting dynamos are generally rather special machines, and so designed that the field is well saturated at the normal working current, and the C R drop in armature and field great, in order that the dynamo should work with a "drooping" characteristic, which is a necessity for the good regulation of such a circuit.

CHARACTERISTIC CURVES.

Characteristic curves, or characteristics, as they are usually called, convey to one experienced in their use very definite information relative to the proportionality of the various parts of the machine to which they refer. Characteristic curves are of two denominations, external and internal ; the former are obtained by plotting the terminal voltage and the current, and the latter by plotting the total voltage generated in the armature coils and the current. To obtain the curve for a given machine it is run at constant normal speed, and the current is varied by varying the resistance in the external circuit. The voltage across the terminals on open circuit is observed, and also when a number of different currents are flowing, the greatest current being the highest the machine will carry without damage ; the results are then plotted as a curve, using the readings of the voltage as ordinates, and of the currents as abscissæ.

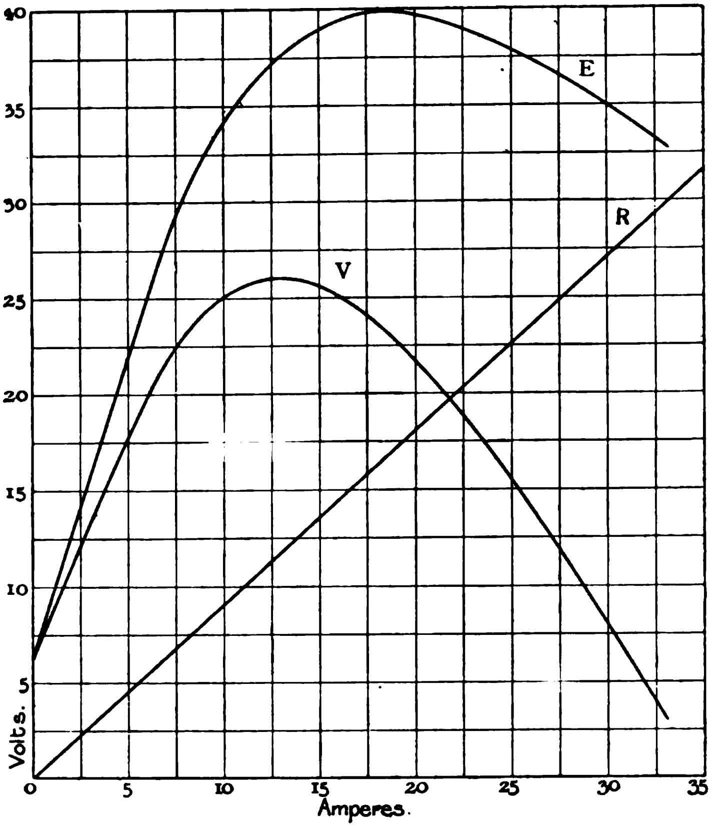


FIG. 405.—INTERNAL AND EXTERNAL CHARACTERISTIC OF SERIES DYNAMO.

SERIES MACHINE.

In the case of a series-wound dynamo the result will be of the same general shape as that marked V in Fig. 405. This curve is known as the "external" characteristic. The "internal" characteristic is obtained from this by adding to it at every point a voltage equal to that lost in the internal resistance of the machine. To do this the internal resistance must be measured and multiplied by the current at every point, giving a result which is shown graphically in the same diagram in the curve R. If now we add the ordinates of the V and R curves together, and plot the sum of voltages for each current strength, we obtain the curve E, and so get the internal characteristic of the machine. It will be noticed that the characteristics do not pass through the origin, but cut the voltage axis above zero, thus indicating that even on open circuit there is a small voltage generated. This is due to the residual magnetism in the poles, from which even the best iron is never absolutely free, and without which it would be impossible to start a series generator except by separate excitation. As the resistance of the external circuit is decreased the current increases, and because the whole current passes through the field coils the magnetism at first increases in direct proportion, since the permeability of the iron is not varying much, and that of the air gap is constant; and the rise of magnetism here gives a proportionate rise in the generated E.M.F. Consequently the first part of the curve is, for all practical purposes, a straight line. As the poles approach saturation the magnetism ceases to be proportional to the current, and falls more and more below proportionality as the current increases, until at last a point is reached when there would be only an exceedingly small increase in flux through the poles, even with an enormous increase of current in the coils. The flux in the poles is not, however, the only factor at work, for as the current increases beyond that giving the straight portion of the curve, the armature reactions become of importance, chiefly because of the increased current, and diminished permeability of the field iron, but also because of the greater lead required by the brushes; these reactions reduce the proportion of the flux usefully threading the armature, and so producing a corresponding decrease in the generated E.M.F. The result is that the curve bends over, becomes flat, and finally droops, this latter effect being due to great preponderance of the armature reactions. In Fig. 405, V is the external characteristic of a series machine. When the external characteristic of a machine has been obtained (by experiment) and plotted, the internal may be rapidly drawn by a simple graphical procedure. If any point be taken on a sheet of squared paper, having one axis of reference ruled to a scale of volts, and another to a scale of amperes, such a point implies a definite resistance value for a circuit to which it may refer. If the point has reference to any circuit

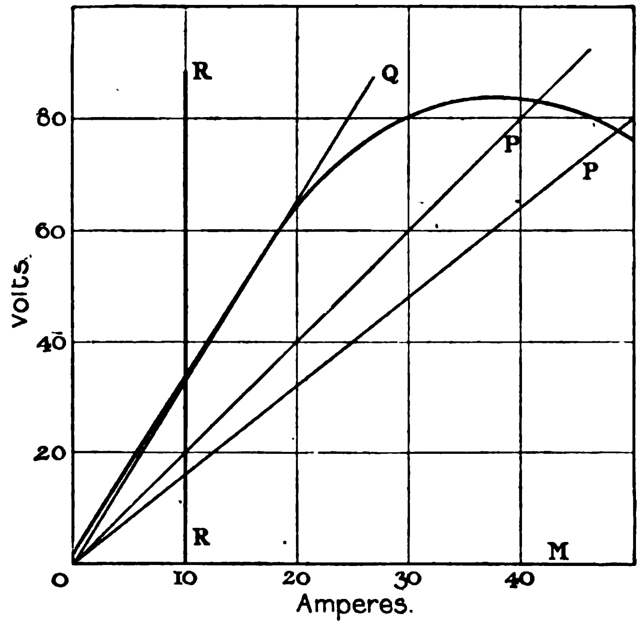


FIG. 406.—RESISTANCE CHART. SERIES MACHINE.

it states that the relationship of voltage and current determined by the position of the point on the paper holds good for that circuit. The actual value of the resistance in ohms is, of course, $\frac{\text{volts}}{\text{amperes}}$. It will be readily seen that if a straight line be drawn from the point considered to the point of crossing of the axes of volts and amperes (assuming that the scales both start from zero), the value obtained for $\frac{\text{volts}}{\text{amperes}}$ is the same for every point on the line (the value of $\frac{0}{0}$ being indeterminate). Further, if a point be taken at some current strength, for a higher resistance the voltage will be higher, and for a lower, lower, and the lines joining such point to the origin will have a steeper or less steep slope respectively; volts being invariably plotted to a vertical scale in such curves. In a word, if the line include the angle θ with the axis of amperes, tan θ = resistance in ohms (of the circuit considered), *if the scales* of volts and amperes *are the same*: if not, then res = κ tan θ, where κ is the ratio of voltage scale to current scale, *i.e.* $\frac{\text{volts per inch}}{\text{amps. per inch}}$.

This is applied to the characteristic curve by drawing a line O R, whose slope gives the internal resistance r of the machine, and is most easily done by taking a point at 10 amperes and 10 × r volts, and drawing a line through this and the origin of sufficient length. Every point on this line then indicates the voltage lost in internal resistance at the current value corresponding with the point. The ordinates of this line at numerous current values are then added to those of the V curve for the same current values, and a new curve, O E, drawn giving the terminal volts plus lost volts for all currents, *i.e.* the "internal" characteristic.

The principle may be further applied by drawing a number of lines, such as O P

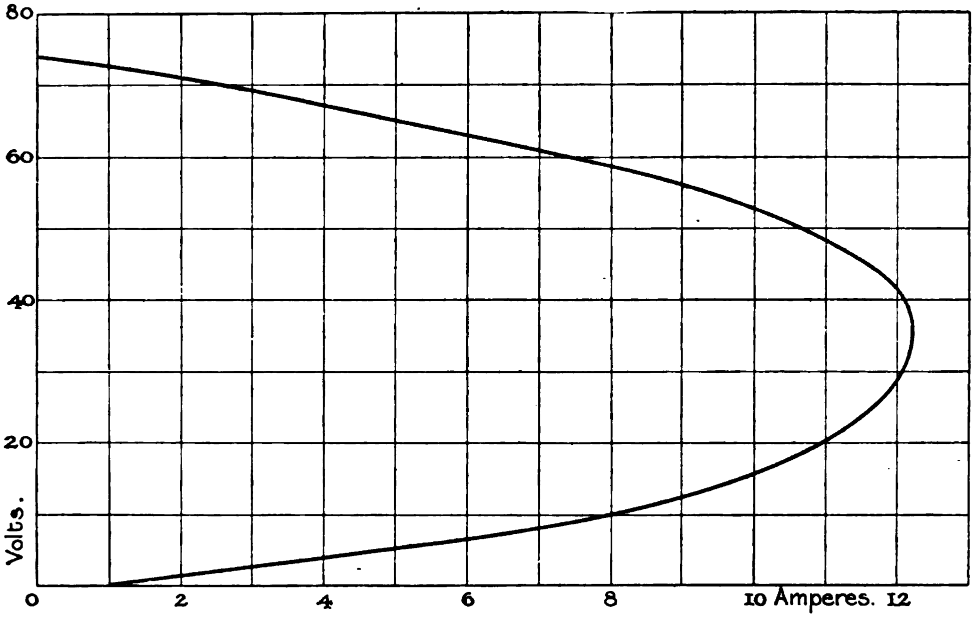


FIG. 407.—EXTERNAL CHARACTERISTIC OF SHUNT DYNAMO.

(Fig. 406) at varying slopes. The point of intersection of any such line and the external characteristic gives the output of the machine when set to work on an external circuit whose resistance is κ tan P O M ohms. The drawing of such lines for several different resistances is facilitated by drawing a line, as shown at R R at a convenient current strength, such as 1, 2, 5 or 10 amperes. Points of R, 2 R, 5 R or 10 R volts, respectively, are then at once taken on it and joined to the origin, giving forthwith the performance of the machine (at the points P, P, etc.) on the circuits referred to. It will be observed that as the resistance increases the point P moves towards the voltage axis until a position such as Q is reached, the voltage and current both decreasing until the resistance reaches a certain value, about 3·8 ohms in this case, when the line O P will be practically a tangent to the straight part of the curve, and a very slight increase in resistance will cause the machine to lose its magnetism, owing to the very large drop in voltage, and consequently in current. The resistance at which this occurs is called the critical resistance of the machine for that particular speed to which the curve belongs; for it must be clear that such resistance will be different at each different speed, since the voltage for a given current varies with the speed. It is sometimes useful to compare the characteristic with the magnetisation curve. To obtain the latter the machine is separately excited, and the voltage at the brushes measured with varying excitations; the curve connecting voltage and exciting current is then plotted on the same sheet as the characteristic. If the curve so obtained is nearly the same as the external characteristic, it is clear that the droop of the curves is due, not to armature reactions, but to the reluctance of the air gap. A little consideration will show that a machine with a small air gap will have a steep magnetisation curve with a fairly horizontal top, owing to the preponderance of the effect of the iron permeability on the total flux.

SHUNT MACHINE.

Similar curves may be obtained in connection with shunt machines. It is usual to plot a curve called the "magnetisation curve," and one called the external characteristic. The magnetisation curve is obtained by supplying exciting current from an independent source and observing exciting current strength and terminal voltage, the speed being kept constant. Volts are then plotted to a vertical scale, against exciting current on a horizontal scale. The curve so obtained is very instructive, since the vertical ordinates, though measured in volts, are a direct measure of flux threading the armature. The slope of this curve is an indication of the relative reluctances of air gap and iron, since, if the former be unduly high, the slope will be less steep than it should be, and the curve will not bend into a more horizontal direction until the exciting current has reached an unduly high value. The curve may conveniently carry two vertical and two horizontal scales, the former giving volts and flux, and the latter current and ampere turns. The external characteristic (Fig. 407) is taken just as with a series machine, terminal voltage being plotted vertically at a constant speed, against varying current in the external circuit, plotted horizontally. The external characteristic of the shunt machine is very different in shape from that of the series, being quite its antithesis, for it rises to its maximum voltage on open circuit. On the circuit being closed through a high resistance which is gradually decreased, the curve is at first a straight line with a slight downward slope, which, as the resistance continues to decrease, increases until in an old type of machine the curve turns round and comes back to the origin in an almost straight line. With a modern design, however, the current required to obtain readings at the bend of the curve is beyond the limit of the machine, since designers always work on the initial straight part of the curve. The reasons for the shape of the curve are as follows: When the machine is on open circuit the field winding takes the whole current generated, and at practically the full generated E.M.F., since the fall of potential in the armature, with so small a current, is practically nil in a well-designed machine. On the external circuit being closed through a high resistance an additional small current is taken, which increases the fall of potential due to armature resistance, and so reduces the terminal voltage. The field winding is connected across the terminals, and there is now, therefore, less voltage available to drive the current through it, hence the shunt current decreases, and with it the field flux and the E.M.F. generated. This tends to react yet further on the shunt current, and it would appear, at first sight, that the cycle of effects must continue until the voltage dropped to zero, no matter how small the external current. Finality, or rather stability, is reached long before such a climax occurs, owing to the fact that the machine is always designed with the iron fairly saturated at no load, so that the flux is by no means proportional to the shunt current, and therefore falls less rapidly than the excitation. Moreover, there is a very slight compensation in the reduced C R drop in the armature as the shunt current falls. If the external current be further increased (by reducing the external resistance) the terminal voltage drops yet further, and after a little thought it will be seen that the greater the armature resistance, the greater will be the slope of the curve. With modern machines the armature resistance is so low that the slope due to it is very slight, and in large machines the straight part of the curve is practically horizontal. The bending and turning of the curve is partly due to the same causes as the bending and turning of the series characteristic, namely, predominance of armature reactions. In contrast with the series machine in which the saturation increases with the load, the shunt machine has a weakening field, so giving greater licence to the armature reactions. The current, when the vertical portion of the curve has been reached, is called the critical current, and the external resistance then the critical resistance for that speed, since any slight decrease of resistance will reduce both current and voltage to almost nothing. Other curves, showing total armature current, *i.e.* external current plus shunt current, or showing total internal voltage, may readily be plotted from the above as occasion may demand, but their use is very limited.

COMPOUND MACHINE.

It will be noticed that with an increase of current, up to a certain point, the terminal voltage of a shunt machine falls, while that of a series rises. Now, frequently it is important to keep the terminal voltage constant, no matter what current is being taken, and it was early realised that by using both a series and a shunt winding on the same machine this result could be obtained. This is called compounding, and is effected by using an ordinary shunt winding, supplemented by a few turns in series with the armature, the result being a nearly horizontal characteristic usually slightly curved. The voltage drop of a shunt machine is caused by armature resistance and armature reactions, and as has already been seen, the latter increases at a greater rate than the armature current. Since the series ampere turns increase only with the current it is clearly impossible to obtain an absolutely horizontal characteristic, although a machine is sometimes said to have one. What is really meant is that the curve rises slightly to, say, a little over half load, and then droops to about normal or no-load voltage at full load, as in Fig. 408. Sometimes, however, a machine is over-compounded, that is, more series turns are put on than are required to obtain a "horizontal" characteristic, the result being that a continuously rising one is obtained instead. This is usually the case with machines supplying distant feeding points, the extra voltage generated being used to make up fort he increased voltage (C R) loss in the feeders, so that the potential difference at the loaded end is kept constant.

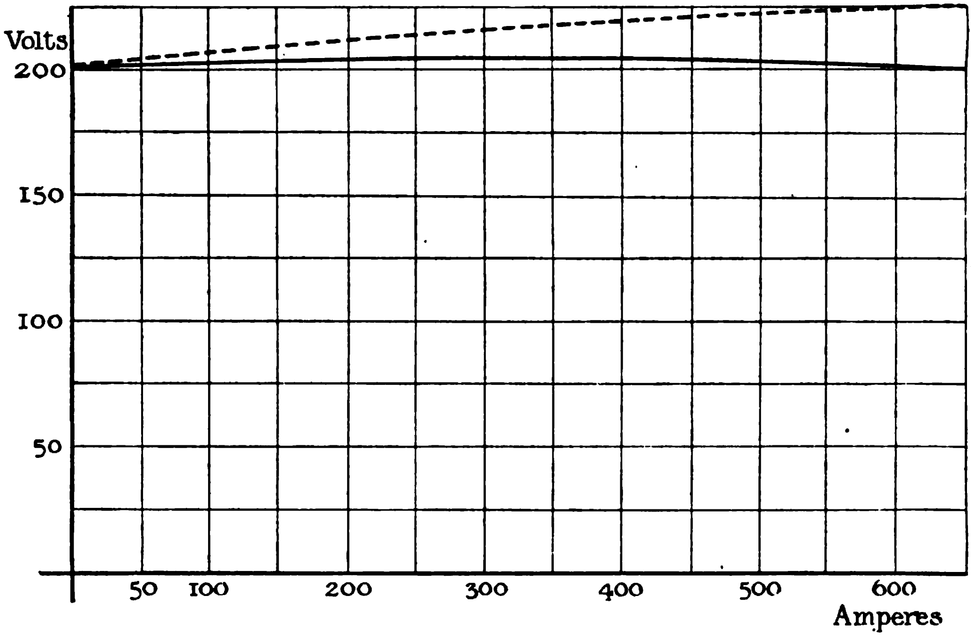


FIG. 408.—COMPOUND DYNAMO CHARACTERISTICS: FLAT COMPOUNDING SHOWN BY FULL LINE, OVER COMPOUNDING SHOWN BY DOTTED LINE.

THE OUTPUT COEFFICIENT.

In working out a design to a given specification, we can, of course, only arrive at the most suitable final dimensions by the exercise of a considerable amount of judgment depending upon the experience of the designer. The best design to fulfil a given specification can only be judged from the commercial standpoint. It is not difficult to design a machine which will give the required output without over-heating or sparking; but to design the *cheapest* form of such machine is not so easy a matter. Dynamo design is an art. and as such much depends on the experience of the designer; and to give precise rules therefore as to how to produce the best design in all circumstances is impossible, and we can only indicate the general lines upon which to proceed.

In order to obtain an approximate size for a machine of any given output, it is convenient to express the kilowatt output in terms of the *volume* of the armature, or in other words:

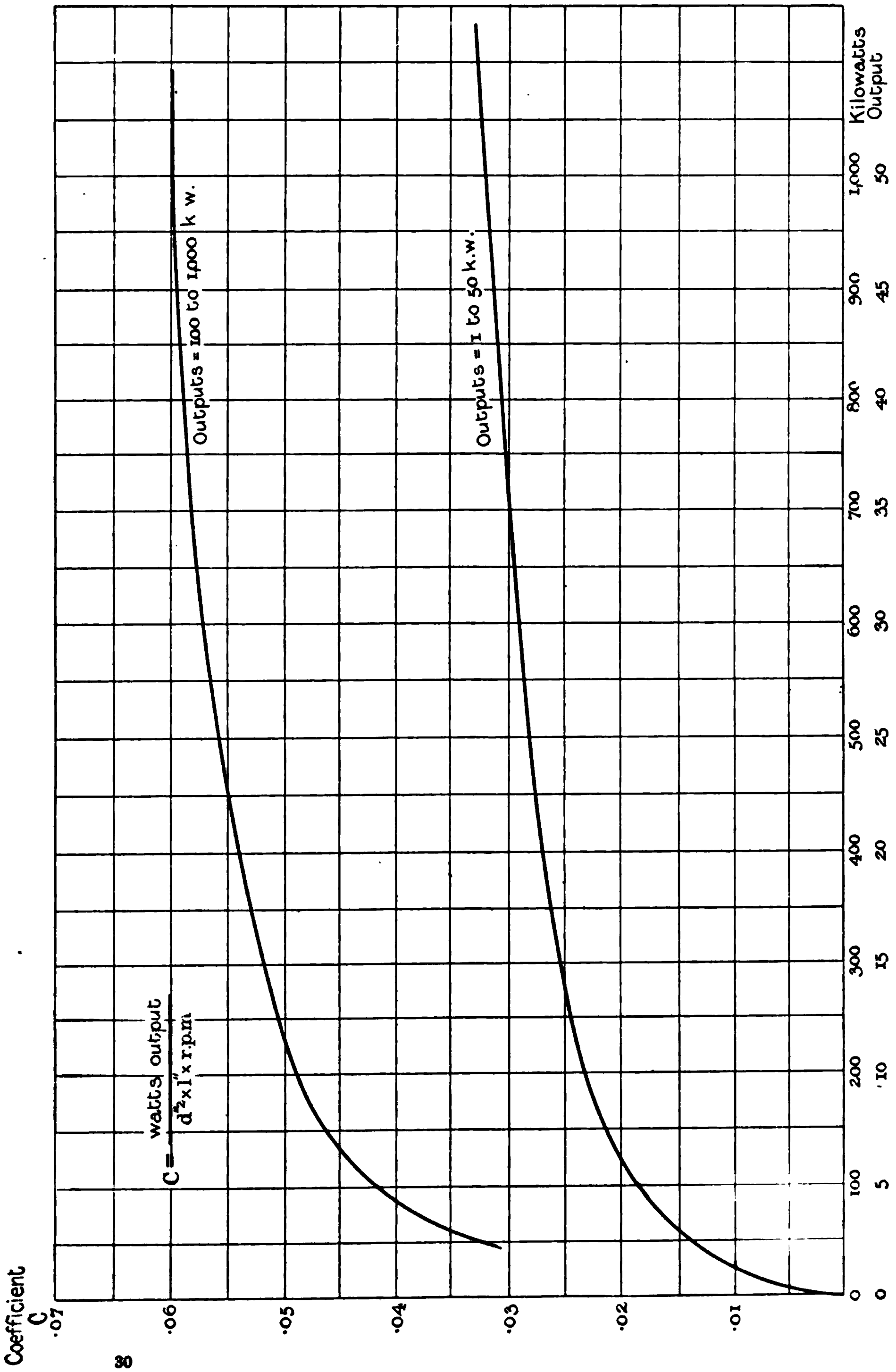


FIG. 409.—OUTPUT COEFFICIENTS CONNECTED WITH OUTPUTS.

$$(\text{Diameter of the armature})^2 \times \text{axial length of armature core},$$

for it is found in practice that the output for a given speed which can be obtained is roughly proportional to this, though, of course, as so many factors enter into the question, such as number and shape of poles, ventilation of the armature, the proportion of active iron and copper used, etc., such comparison can only be regarded as approximate.

Consider an armature of a given diameter and given axial length, revolving at a definite speed, and assume that from this armature we get a certain definite output in kilowatts, we can then ask ourselves what output we should expect to get if we doubled the diameter of the armature, keeping the axial length and the speed in revolutions per minute the same. By doubling the diameter we have doubled the surface of the armature, and we are thus able to introduce double the total number of magnetic lines into the armature, and are able, therefore, to double the total voltage induced in the armature, if we keep the same number of conductors. At the same time we are able to double the current in amperes by doubling the sectional area of each individual conductor. Or, if we had halved the total number of conductors when we doubled the diameter of the armature, we should have been able to make the section of each conductor four times what it was at first. As the voltage generated would be the same, we should have increased the output four times, and the number of ampere-conductors per unit length of the periphery would not have been increased.

As a matter of fact, by doubling the diameter of the armature, and keeping everything else the same, we should probably more than quadruple the output, as with the bigger diameter we should be able to ventilate the machine better and use a slightly higher armature reaction, and in other ways to further increase the output. If we work out the value of C in the formula:—

$$C = \frac{\text{watts}}{d^2 \times l \times \text{revolutions per minute}}$$

where d = diameter of the armature in inches and l = the gross core length for a number of actual designs from a small machine of one or two kilowatts up to a large generator of say 1,000 kilowatts, we shall find that the value of this constant will gradually increase owing to the fact that, when we increase

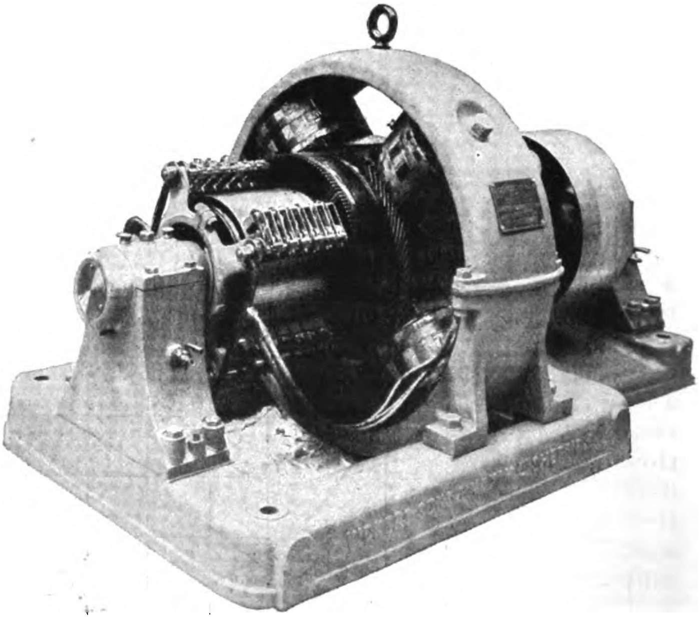


FIG. 410.—FIFTY KILOWATT FOUR-POLE BELT-DRIVEN GENERATOR, BY VICKERS, SONS AND MAXIM.

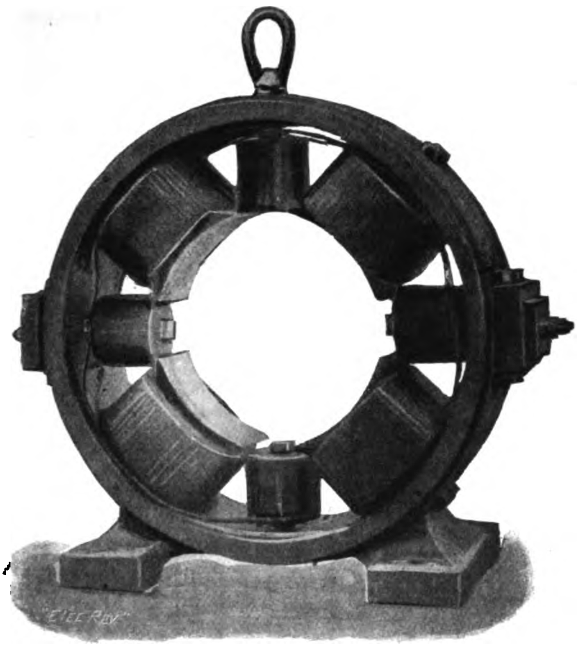


FIG. 411.—FIELD MAGNET OF FOUR-POLE GENERATOR WITH AUXILIARY POLES, BY PHOENIX DYNAMO COMPANY.

the size of machine, as we have seen, the output obtained is more than proportional to the square of the diameter.

The curve in Fig. 409 gives the values of this constant for normal well-designed continuous-current dynamos. Such a curve as this is very useful in comparing designs, though it must be remembered that two machines of the same output may be equally cheap and yet show a considerable difference in the value of this constant, due to different construction, *i.e.* round or square poles, or a different distribution of the active materials.

A dynamo of 50 kilowatts by Vickers, Sons and Maxim is shown in Fig. 410. This machine has an outboard bearing to support the driving pulley, and thus relieve the pulley end bearings of strain and undue wear. The yoke is of cast steel, with steel poles bolted on, and the divided yoke is, of course, a very useful feature, facilitating erection of the machine and inspection of the armature.

The Phœnix Dynamo Company, Limited, were amongst the first makers in this country to use commutating poles extensively on their standard lines of machines, and Fig. 411 shows a four-pole dynamo with auxiliary poles. Fig. 412 shows the armature of this machine, and inspection of this illustration will show that particular attention has been paid to efficient ventilation. There are two ducts through quite a short core, and it will be noticed that special care has been given to the end windings, a perfectly free passage for air being allowed just outside the armature core (where there is often little provision made for free ventilation in many machines), and this is of importance, as the air thrown out at the ends of the armature is very effective in cooling the

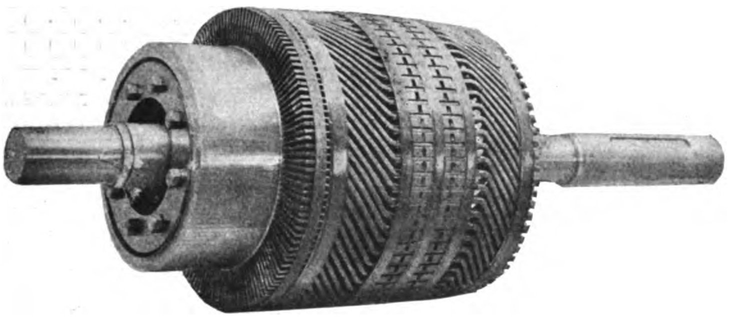


FIG. 412.—ARMATURE OF FOUR-POLE MACHINE SHOWN IN FIG. 411.

field coils. By this excellent ventilation, and the use of commutating poles to raise the sparking limit, the output of this machine was increased considerably. They state that though designed along the ordinary lines for an output of 30 kilowatts, at 550 volts and 525 revolutions per minute, on test it was found that sparkless commutation was not obtained without the commutating poles, even with an air gap 4·5 millimetres long; whereas with the air gap reduced to 2·5 millimetres, and commutating poles fitted, a continuous output of 33 kilowatts could be obtained, and the load could be increased momentarily to 99 kilowatts without any sign of sparking. It was further found that this particular machine could be run up to 1,000 revolutions pei minute, giving 1,000 volts (with a resistance in the field circuit), and even under these conditions of voltage and speed, the auxiliary poles gave sparkless commutation.

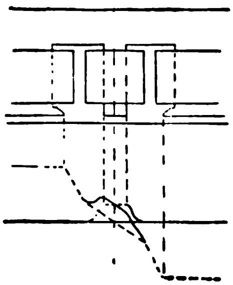


FIG. 413.—DIAGRAM OF FIELD DUE TO MAIN AND AUXILIARY POLES.

Running as a motor with 440 volts on the armature and 500 on the field, the speed at full load could be regulated from 350 to 900 revolutions per minute, simply by inserting resistances in the field circuit.

The diagram shown in Fig. 413 serves to illustrate the action of the auxiliary poles in providing a commutating field between the main poles; the fields due to the main and auxiliary poles are projected on to an axis line. If the auxiliary poles were not present, distribution of the field between the poles would be as the dotted line cutting the origin of the horizontal and vertical axes, as shown; whereas the effect of the "interpoles" is to provide an additional field just at this point, as shown by the unbroken line.

This firm has patented a ventilated field coil, which is shown on a pole-core in Fig. 414. This is a six-pole belt-driven dynamo with three bearings, with a particularly neat design of brush gear and long commutator for a fairly low voltage. The illustration of one of these coils shows how air ducts are provided through the winding in two directions. By this means a great reduction in temperature is attained, and the necessarily increased mean turn of the windings is more than compensated for by the much better cooling, so that for the same weight of copper the temperature rise is still lowered with the ventilated coil (Fig. 415).

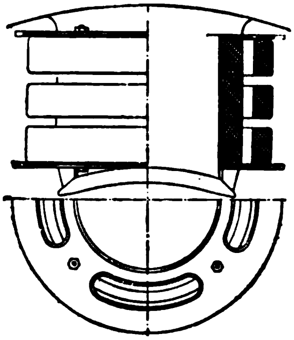


FIG. 414.—PLAN AND SECTIONAL ELEVATION OF VENTILATED FIELD COIL IN POSITION ON POLE CORE.

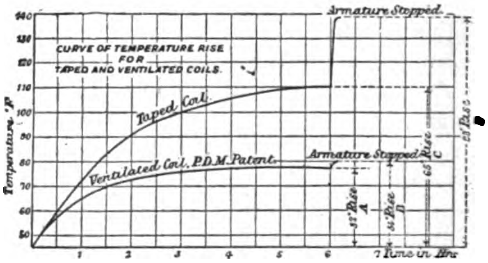
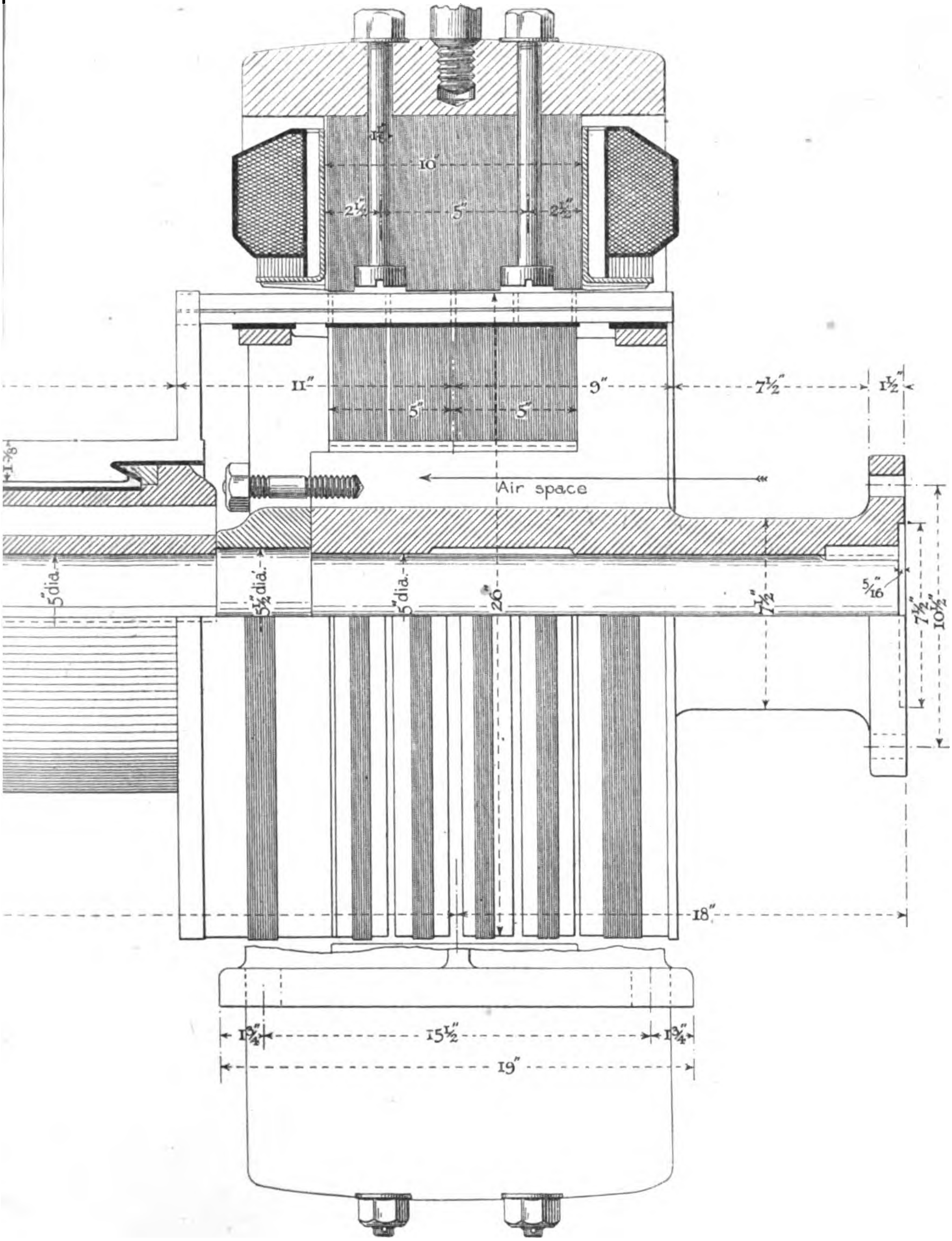


FIG. 415.—TEMPERATURE TESTS ON VENTI LATED AND ON ORDINARY TAPED FIELD COILS.



AT 100-105 VOLTS. (*See page* 469.)

Tests on these coils compared with the ordinary taped coils gave the results shown in the form of curves in Fig. 415. In the case of the machine referred to, which was tested with both types of coil, it was found that the final temperature (owing to the absence of the fanning action of the armature and greater temperature in the interior of the coil) was much greater with the taped coil.

Analysis of 105 *kilowatt dynamo built by Messrs. Laurence Scott and Co., Limited, Norwich.*

Messrs. Laurence Scott and Co., Limited, have kindly supplied full drawings and winding details of one of their six-pole dynamos for direct coupling, shown in Plate II. The output is 105 kilowatts at 400 revolutions per minute, at a pressure of 105 volts, the current output being thus 1,000 amperes. This machine is compound wound and is designed to give 100 volts at no load and 105 volts at full load, that is, it is 5 per cent. over-compounded at constant speed, as is usual with direct-coupled sets. This is done in order that the pressure shall remain practically constant under sudden fluctuations of load, in spite of the slight drop in the engine speed when a sudden load is put on the dynamo ; the slight rise in voltage given by the dynamo running at constant speed thus compensates for the slowing up of the engine. The over compounding of the dynamo is slightly in excess of what is needed for this alone and hence would also suffice to compensate for the voltage drop in the lighting feeders.

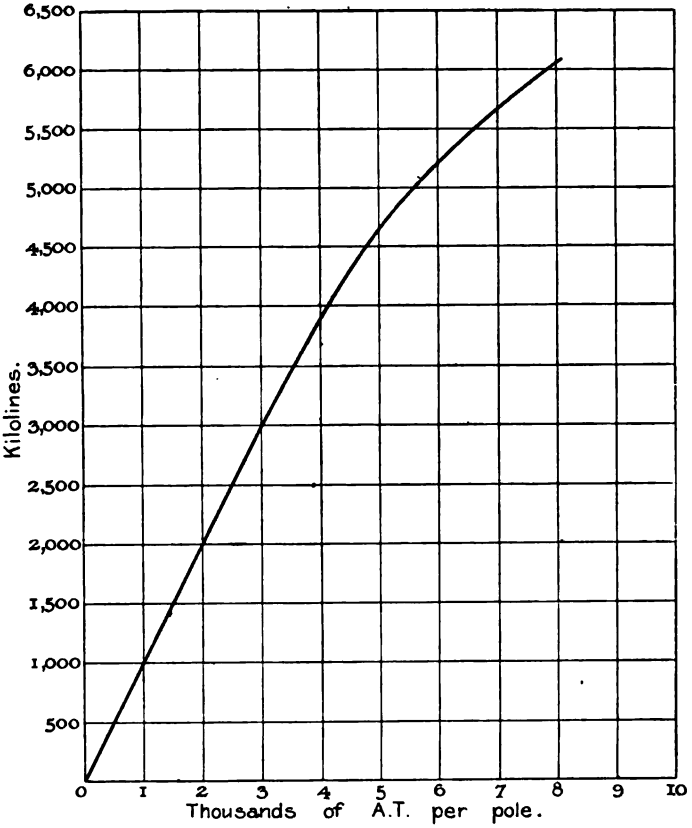


FIG. 416.—MAGNETISATION CURVE OF DYNAMO SHOWN IN PLATE II.

Full detail drawings of this dynamo are shown in Plate II., and saturation curves and core losses in Figs. 416 and 417.

The yoke is of cast steel, the poles being laminated and attached to the yoke, each by two bolts 1⅛ in. diameter, passing right through the body of the pole, the bolt heads being sunk into recesses in the pole face.

The armature core is assembled on an eight-armed, cast-iron spider, this spider being prolonged to form the coupling, and the driving torque thus transmitted principally through the spider and not through the shaft alone.

The armature plates are threaded on to the spider from the commutator end, and are supported at the coupling end by radial arms cast with the spider, the whole being finally clamped up at the commutator end by an end plate with similar arms, eight in number, this end plate being secured to the spider by studs. There are three ventilating ducts through the armature core, and the whole construction permits of very good ventilation, there being free access of air to the armature core at the ends, which is not always the case when the more usual form of annular end plate is employed.

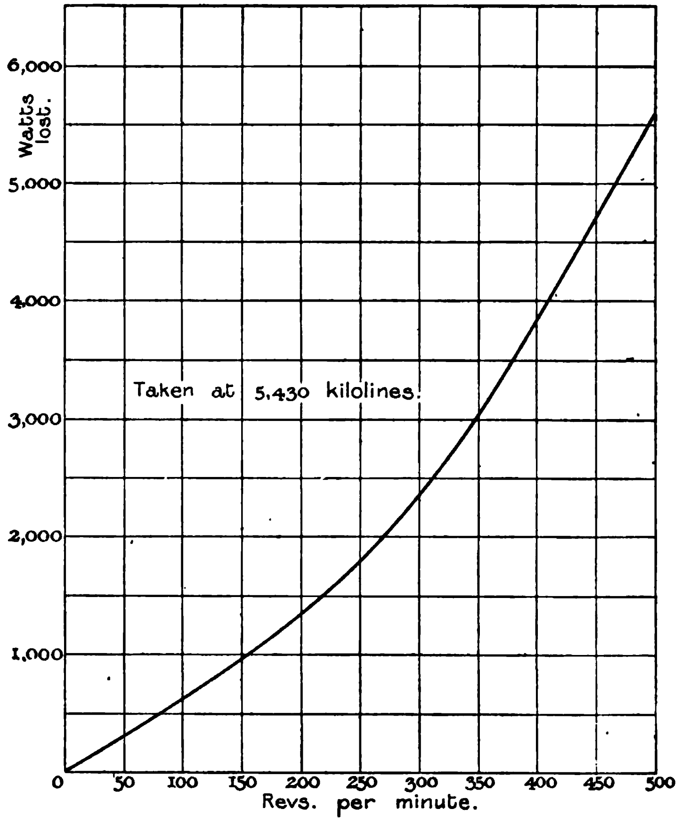


FIG. 417.—CORE LOSSES BY HYSTERESIS, EDDY CURRENTS, WINDAGE AND FRICTION IN ARMATURE OF MACHINE SHOWN IN PLATE II.

The commutator is built up in a cast iron sleeve secured to the shaft by a feather key, the commutator bars being tightened up by the usual type of ending.

Phosphor-bronze bearings with spherical seatings are used, lubrication being effected by means of the usual oil rings running in an oil bath.

The commutator is very long owing to this being a low-voltage lighting generator, the current at each brush spindle being 1,000 ÷ 3 = 333 amperes.

The armature is 26 in. in diameter, with a gross core length of 10 in., and the d^2l constant is thus :—

$$\frac{105000}{(26)^2 \times 10 \times 400} = 0{\cdot}039.$$

There are 76 slots each 1·4 in. deep and 0.44 in. wide, with four conductors in each slot (*see* detail drawing, Plate II.). There are thus 304 conductors in all on the armature with one turn per commutator segment, which means 152 segments in the commutator, the winding being of the parallel or lap variety, with six circuits through the armature. The current per circuit will therefore be 1,000 ÷ 6 = 167 amperes nearly.

Though this is a bar winding, laminated strip has been used for the armature conductors, these conductors each being built up of nine copper strips in parallel, each strip being 0·14 in. × ·06 in. which means a total copper section of .075 square in., and as there are 167 amperes per circuit the current density in the armature at full load (neglecting the shunt-exciting current, which the armature must provide) is about 2,239 amperes per square inch.

As we have mentioned, it is not usual in a bar winding such as this to use laminated strip, a solid strip being generally used, as laminated strip of the same section is more expensive; but the laminated strip of course gives greater flexibility and freedom from eddy currents, and the makers doubtless have good reasons for its adoption in this particular case.

The magnetic flux at no load existing in each pole will be, using the formula:—

$$N = \frac{E \times 10^8}{Z n} \times \frac{p}{c} = \frac{100 \times 10^8}{304 \times \frac{400}{60}} \times \frac{6}{6} = 4{\cdot}9 \times 10^6 \text{lines.}$$

In order to calculate the excitation taken by the machine at full load, we must ascertain the internal volts necessary to be generated in the armature at full load, so that the machine may give 105 volts at its terminals. The internal voltage generated at full load will be greater than this by the lost volts or CR drop in the armature, and there will also be the drop in the series winding, and the drop of about 2 volts at the carbon brushes to add to the armature drop.

The makers give the armature resistance (all circuits in parallel) as 0·0026 ohms at 140° F., and as the total current is 1,000 amperes, the CR drop is therefore $1{,}000 \times 0{\cdot}0026 = 2{\cdot}6$ volts.

Similarly the resistance of the compound winding being 0·000545 ohms at 130° F., the CR drop will be 0·545 volts.

We have thus as the total voltage to be generated in the armature at full load $105 + 2{\cdot}6 + 0{\cdot}545 + 2$ (drop at brushes) $= 110{\cdot}145$ volts or, in round numbers, say 110 volts.

The flux existing in the armature when the dynamo is giving 1,000 amperes at 105 terminal volts and 400 revolutions per minute must therefore be:—

$$4{\cdot}9 \times 10^6 \times \frac{110}{100} = 5{\cdot}4 \times 10^6 \text{ lines.}$$

The flux in the poles and yoke will of course be greater than this owing to the magnetic leakage.

The leakage coefficient of this machine is given as 1·15, a very reasonable figure for this size and type of machine. This gives for the flux existing in the field at no load $4{\cdot}9 \times 10^6 \times 1{\cdot}15 = 5{\cdot}63 \times 10^6$ lines and at full load $6{\cdot}05 \times 10^6$ lines.

We must now, in order to calculate the total excitation of the machine, ascertain the magnetic density in each part of the magnetic circuit, and having done this make use of such magnetisation curves as are given in Chapter I. to ascertain the ampere turns per inch length required according to the material used in the portions of the magnetic circuit considered. The length of path in each part of the circuit is then measured on the drawings; from these lengths and the ampere turns per inch for each part as given by the curves, the total ampere turns for each part and the whole circuit are evaluated.

The magnetic tables which we give on page 473 for 100 volts at no load and 110 volts at full load are calculated for one pole, and give the ampere turns required at these two voltages. In order to obtain the total excitation with 105 volts at the terminals at full load we of course have to add to the ampere turns required to generate the 110 internal volts (corresponding to 105 volts at the terminals at full load) the ampere turns required to compensate for the demagnetisation and distortion produced by the reaction of the armature currents on the field.

The path of the magnetic flux in a multipolar dynamo has been explained by means of Fig. 394 in Chapter II. It is obvious from this illustration that the flux entering the armature from a pole divides when it reaches the armature core into two branches, the pole flux flowing right and left through the armature core, and returning to the field coil through the two adjacent poles. If we take the whole flux from, say, a N pole, this flux entering the armature will return to the field through the two adjacent S poles. Thus only half the flux from a pole flows through the single section of the armature core and yoke, and therefore in constructing a magnetic table, if we consider the total flux throughout in respect to the areas of the different portions of the magnetic circuit, we must double the areas of the yoke and armature core in order to get the correct density in these parts.

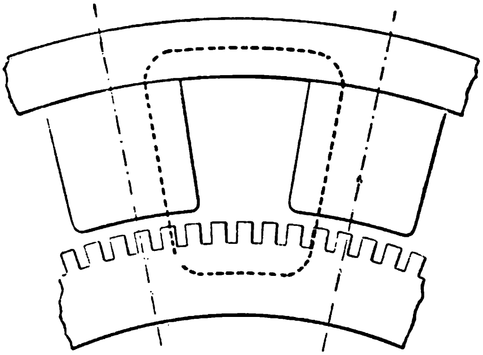


FIG. 418.—MEAN MAGNETIC PATH IN MULTIPOLAR DYNAMO.

The correct mean magnetic path to be taken is shown by the dotted line in Fig. 418. The closed circuit given by this line gives the magnetic lengths to be considered per pair of poles. For the calculation of one pole winding only we take half this as indicated by the dotted line. Thus, for the calculation of one pole, the lengths of magnetic path to be considered and the areas of the various parts using the total flux from one pole are :—

Part.	Magnetic area.	Magnetic length.
Armature	Double area	Half length
Teeth	Single area	Single length
Air gap	Single area	Single length
Pole	Single area	Single length
Yoke	Double area	Half length

Thus we construct the following magnetic tables, obtaining the density in each part and the magnetic lengths as above, finally obtaining the total ampere turns for each part in the last column. These are practically, as we have pointed out, the values taken from the makers' table, and if the magnetisation curves given in this work in Chapter I. are used for the calculation, approximately the same total excitation will be obtained.

In the case of the teeth the magnetic densities given are "equivalent" densities. If the apparent densities at the roots of the teeth had been taken (the area of 37·2 square in. is the area at the root of the teeth) the excitation calculated would be greater than the actual excitation, for the reasons given in Chapter I.

The saturation curves given in Fig. 416 which were actually taken from the dynamo when built, show that at 100 volts the excitation was 5,500 ampere turns per pole and at 110 volts 6,500 ampere turns per pole, these actual values being about 8 per cent. higher than given by the calculated values. Such discrepancies as these are usual, due to slight variations in the air gap, quality of materials, etc., and are provided for by always allowing some little margin in the resistance of the shunt winding, the surplus voltage being taken up by the shunt regulator.

The field winding of this dynamo consists, for the shunt of 498 turns per pole, of No. 10 S.W.G. copper wire (diameter =0·128 ins.).

Now the shunt winding has to provide sufficient ampere turns to give 100 volts when the machine is running at 400 revolutions per minute. We see that according to the saturation curve obtained on test, the ampere turns required are 5,500, and, therefore, there being 498 turns, the shunt current will be 5,500 ÷ 498 = 11 amperes.

The shunt coils are slightly coned, and the mean length of one turn of the wind-

100 volts $Na = 4{\cdot}9 \times 10^6$ $Nm = 5{\cdot}63 \times 10^6$.

Part.	Flux.	Area.	Density.	Mag. length.	Ampere turns per inch.	Total ampere turns.
Armature	4,900,000	77·6	63,000	5	9	·45
Teeth	4,900,000	37·2	125,000 (Eq.)	1·4	540	755
Air gap	4,900,000	92·5	53,000	¼	16,300	4,080
Pole	5,630,000	85·5	66,000	8½	12	102
Yoke	5,630,000	94	60,000	11½	9	104

Total ampere turns per pole = 5,086.

110 volts $Na = 5{\cdot}4 \times 10^6$ $Nm = 6{\cdot}05 \times 10^6$.

Part.	Flux.	Area.	Density.	Mag. length.	Ampere turns per inch.	Total ampere turns.
Armature	5,400,000	77·6	70,000	5	11	55
Teeth	5,400,000	37·2	140,000 (Eq.)	1·4	780	1,090
Air gap	5,400,000	92·5	58,500	¼	18,350	4,600
Pole	6,050,000	85·5	71,000	8½	16	136
Yoke	6,050,000	94	64,500	11½	12	138

Total ampere turns per pole = 6,019.

TABLES SHOWING METHOD OF CALCULATING EXCITATION REQUIRED.

ing is 47·5 in. or 3·95 feet. The total length of wire on one pole is therefore 3·95 × 498 = 1,960 feet, and referring to our table in Chapter I. of the properties of copper wires, we find that 0·128 in. diameter wire has a resistance, at 45° C. of 0·70 ohms per 1,000 feet, therefore the total resistance of the winding on one pole is 0·70 × 1·96 = 1·37 ohms, or for the six poles (all the shunt coils being in series) the resistance is 1·37 × 6 = 8·2 ohms. As at no load the voltage of the machine is 100 the maximum current which can flow through the shunt winding is therefore 100 ÷ 8·2 = 12·2 amperes.

We thus have some margin of excitation so that when all resistance is out of the shunt regulator we can get about 110 volts at the terminals at no load.

The current density in the shunt winding with 11 amperes flowing is 860 amperes per square in., and the temperature rise on test was 50° F. as measured by thermometer after a six hours' run.

The series winding consists of 6½ turns per pole of copper strip 1 in. × 0·3 in. in section, having thus a cross-sectional area of 0·3 square in., and owing to the heavy full load current of 1,000 amperes the series windings are put in three parallels, the current through the windings on each pole being 333 amperes, giving a current density of 1,110 amperes per square in. at full load. This gave a measured temperature rise of 45° F. after the full load run.

The series ampere turns per pole are 2,160, and as the no-load voltage of the dynamo is 100 and full load 105 volts, the series winding provides sufficient ampere turns to increase the voltage from no load to full load to this extent, in addition to compensating for the voltage drop in the armature, brushes, and the series winding itself. We have found that these various drops amount to 5 volts. The series winding has thus to provide the difference between the ampere turns required per 100 and 110 volts, and must also effect the necesary compensation for the armature reaction.

The difference between the ampere turns at 100 and 110 volts is from the saturation curve about 1,000 ampere turns (6,500 − 5,500), thus leaving 2,160 − 1,000 = 1,160 for the armature reaction.

The accurate calculation of the armature reaction can only be made if we know the position of the brushes, and the necessary allowance for the reaction component of the series ampere-turns will depend to some extent upon the commutating properties of the design, that is, if the reactance voltage is high, the brushes will be given a large "lead," and this will give the maximum reaction of the armature in the field. The reactance voltage of this dynamo is low, hence the brushes could be placed not far from the geometrical neutral position, ensuring a minimum reaction.

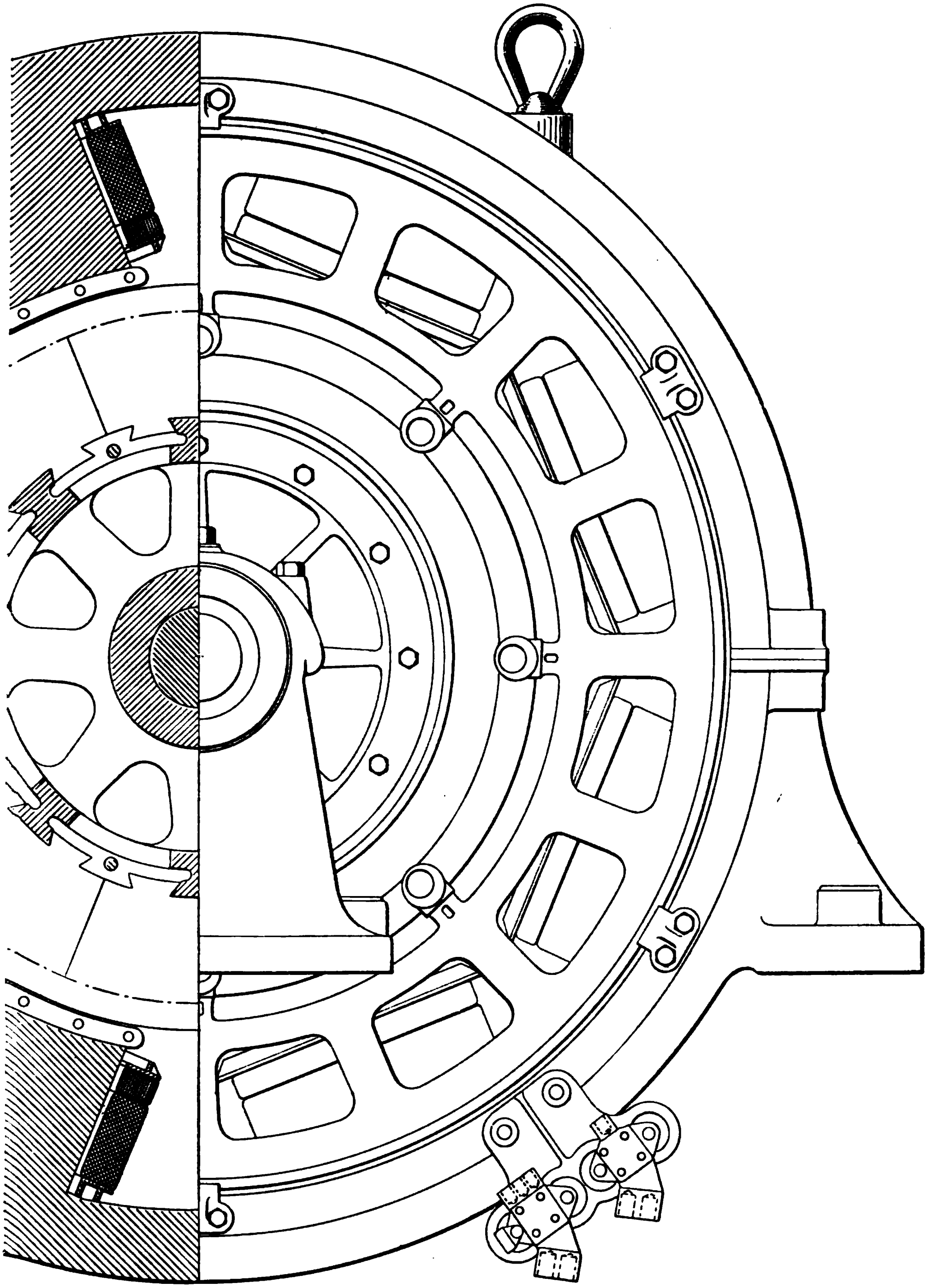
Fig. 419 shows a photograph of an 8-pole 500 kilowatt standard generator for direct coupling by the Electric Construction Company, Limited, of Wolverhampton. The output is 500 killowatts at 500–550 volts at a speed of 350 revolutions per minute. The machine has one end bearing and engine coupling which is not shown in this view, and no bedplate is provided, as these large direct-coupled generators are invariably mounted on an extension of the engine bedplate provided by the engine makers, the dynamo manufacturers supplying the end bearing only.

There are eight brush spindles and eight brushes per spindle, the brush spindles being supported from the brush rocker in the centre, and this is an excellent arrangement, as it insures equal distribution of the current between the different brushes, trouble often being experienced with very long brush spindles with no such central connection, from the brushes not sharing the current equally, the brushes at the collecting end of the spindle often carrying an undue share of the current while those at the other end may carry very little. This form of brush rocker carried from the yoke of the machine ensures, as a rule, steadier running on the commutator than when the brush rocker is supported on the end bearing. The yoke of the dynamo is of cast iron, with bolted on poles, the bolts being countersunk to add to the finish of the machine; and generally the design is very neat.

A sectional drawing of a standard 8-pole 600 killowatt 300 revolutions per minute 500 volt machine by the Lancashire Dynamo and Motor Company, Limited (Plate III.), gives a good general idea of the constructional details of a modern direct-coupled generator.

This machine is compound wound, the series winding being placed next the pole tip, as was the case with the Laurence Scott 6-pole dynamo which we have already analysed. This is a better arrangement than to place the series coils next to the yoke, as in this case the magnetic leakage from the poles is greater when load comes on, and it is found in practice that more series winding is required than when the coils are placed next the pole tip. The general design is similar to the E.C.C. dynamo which we have just described, the brush gear being carried from the yoke; in this case, however, the brush spindles are supported at *both ends*, and each spindle is independently capable of some movement along the commutator. This is a useful feature, as it is desirable that the brushes on different spindles should not be exactly in line, in order that the wear should be distributed over the commutator. The yoke and poles of this machine are in one piece in cast steel, with laminated pole tips bolted on, and this is probably the cheapest construction to adopt, as the amount of machining necessary is reduced to a minimum.

The armature core is built up of segments threaded on to a cast-iron spider provided with notches on its external



ɪOTOR COMPANY. (*See page* 474.)

periphery as shown; this segmental construction of the armature core is usual in machines exceeding 36 in. or 40 in. in armature diameter, as iron plate is not rolled in widths much exceeding this, and for other reasons it is cheaper to adopt the segmental construction when these diameters are exceeded. The engine coupling is provided for by an extension of the cast-iron spider, so relieving the shaft of driving strain when running, and permitting a smaller shaft diameter. Four ventilating ducts are run through the armature core, and band spaces for the reception of steel binding bands are shown, there being five bands in all along the core.

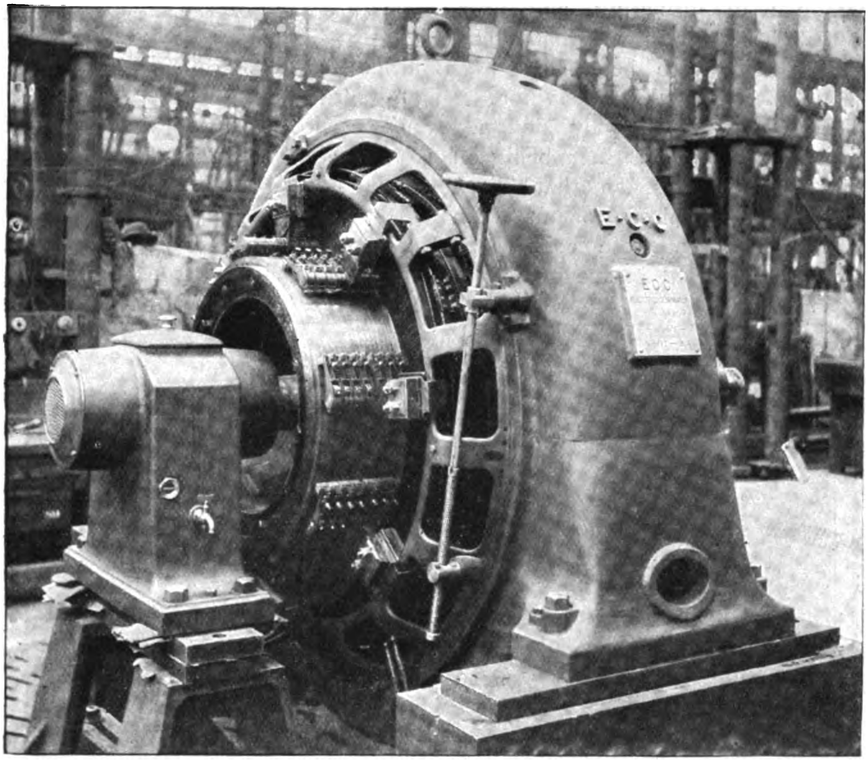


FIG. 419.—DIRECT DRIVEN 500 KILOWATT GENERATOR, BY THE ELECTRIC CONSTRUCTION COMPANY, LIMITED.

The next machine which we describe, and illustrate by two excellent photographs, (Figs. 420 and 421) kindly supplied by the makers, Messrs. Vickers, Sons and Maxim, Limited, of Sheffield, is driven by a 2,000 horse-power gas engine made by Messrs. Beardmore and Co., Glasgow. It is a 1,400 kilowatt shunt wound 24 pole dynamo running at 100 to 105 revolutions per minute, and giving 3,050 amperes at 460 volts. The poles are bolted to a yoke of inverted **T** section in Beardmore's high permeability magnet steel.

The armature is 13 feet in diameter and weighs 17 tons, the armature core being carried from a cast-iron spider by 22 arms, each of these arms being separately bolted on. The makers have furnished the following description of this machine :—

The armature coils are former wound and interchangeable; the high-conductivity copper bars are accurately formed to shape, taped, dried and waterproofed, then wrapped in insulating and overlapping troughs of mica, presspahn, and leatheroid, which have been previously dried and waterproofed. The whole is pressed together in specially designed heated presses to ensure their being an exact fit for the slots, so that slight pressure only is required to put them into place. The complete coils, after being thoroughly dried in vacuum ovens and finally waterproofed and dried again are placed in their respective slots without further insulation. These coils are secured in place by wooden wedges through the slots, and by strip-steel bands on the end winding.

The commutator is carried on a separate cast-iron sleeve, which is bolted to the armature hub. It is built up under an hydraulic press at a pressure of 50 tons per square in., the lugs being riveted and sweated into the hard-drawn copper plates, and rigidly held together in groups and anchored to insulated pins fixed to the armature casting. The brush spindles are carried by saddle pieces, which support the

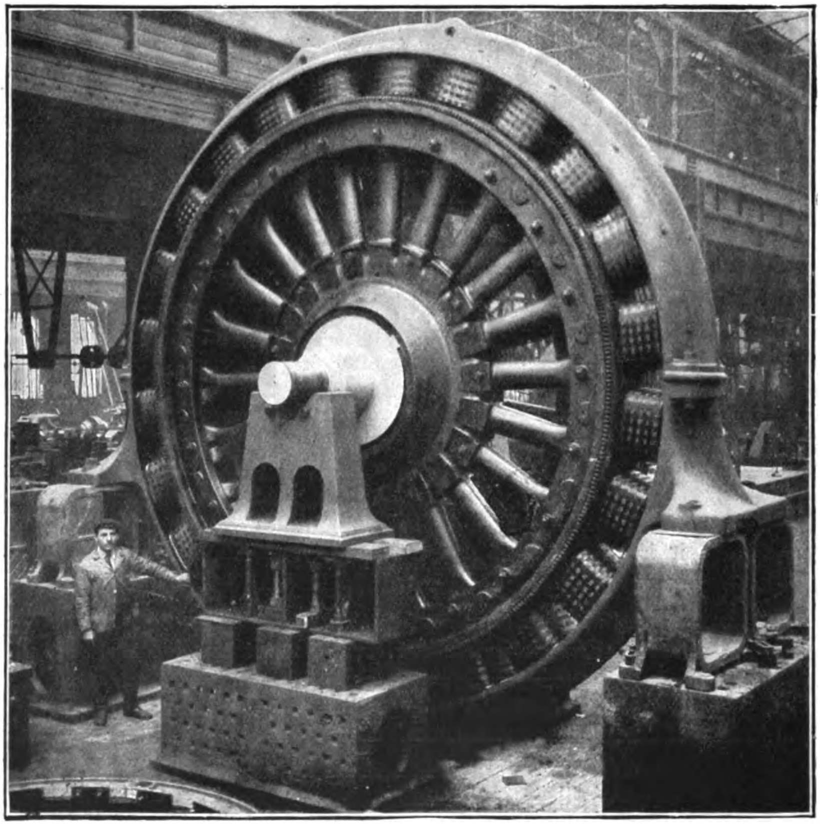


FIG. 420.—FIELD MAGNET AND ARMATURE OF 1,400 KILOWATT DYNAMO, BY VICKERS, SONS AND MAXIM.

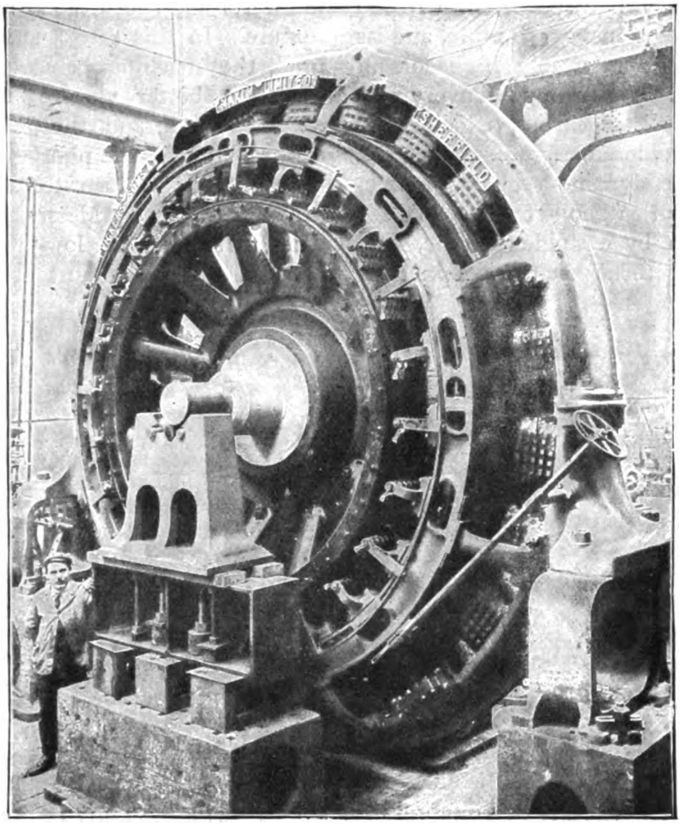


FIG. 421.—SHOWING COMMUTATOR AND BRUSH GEAR IN POSITION ON THE DYNAMO SHOWN IN FIG. 420.

spindle in two places, and these are bolted to, and insulated from, a rocking yoke, which, in turn, is supported by eight arms from the magnet frame, and rocked by a worm and hand wheel. This rocking yoke and the collector rings are made of large diameter, so as to give ready access to the brushes.

The brush holders are of the sliding-box type, with hinged clamps, so that any brush holder can be removed without disturbing the others.

The extensive employment nowadays of the steam turbine has created a demand for extra high-speed dynamos, but it cannot be said that the continuous-current machine has been very extensively employed in this connection, owing to the very serious difficulties which have to be overcome in the design of high-speed generators when commutators have to be employed. However, a considerable number of continuous-current turbo-dynamos are already in use, and their number is growing, despite the fact that the greater demand is for turbo-alternators.

Some of the most successful continuous-current machines of this type have been built by Messrs. Greenwood and Batley of Leeds, who are the makers of the De Laval steam turbine in this country. These turbines are of the single-impulse type and run at extremely high speeds, from 10,000 to 20,000 revolutions per minute, and as this speed is impracticably high for an electric generator, they employ a very perfect type of helical gearing, reducing the speed to a moderate figure. Fig. 422 shows a double dynamo set of 150 kilowatt output at 1,000 revolutions per minute, driven by a single turbine, this duplex arrangement being adopted as being particularly suitable to the running of the reducing gear. The pinion on the shaft of the turbine wheel runs between the two slow-speed gear wheels, one of which is coupled to each of the dynamos, the gear box being shown in the middle of the photograph.

The commutators of the dynamos are of small diameter, and carbon brushes are employed, as these machines are of comparatively low speed for turbine work, and the employment of carbon brushes is here possible, but copper brushes are found necessary with the very high speed turbo-dynamos.

A smaller set by the same makers is shown in Fig. 423, the output being 20 kilowatts and speed 2,000 revolutions per minute. In this case a single dynamo is used, the machine being of the bipolar type. A better view of the turbine is obtained here, and the gear box is seen in the middle of the photograph.

In Fig. 424 is illustrated a large turbine-driven dynamo by Messrs. Siemens Bros. The turbine is a low-pressure Rateau turbine, taking exhaust steam from the non-condensing mill engines of the Steel Works Company, of Scotland, to whose order the set was built; the turbine was built by Messrs. Fraser and Chalmers. The normal output of the set is 450 kilowatts at 1,500 revolutions per minute; this is effected with 2,000 amperes at 230 volts. For the collection of so large a current at this speed, and to also retain the use of carbon brushes and their advantages, a very long commutator is needed. The commutator really consists of two, placed side by side with a gap between them. Every bar is made of two parts, each of which is recessed, so that when placed together a hollow duct is formed right through the bar. In the gap fans are pro-

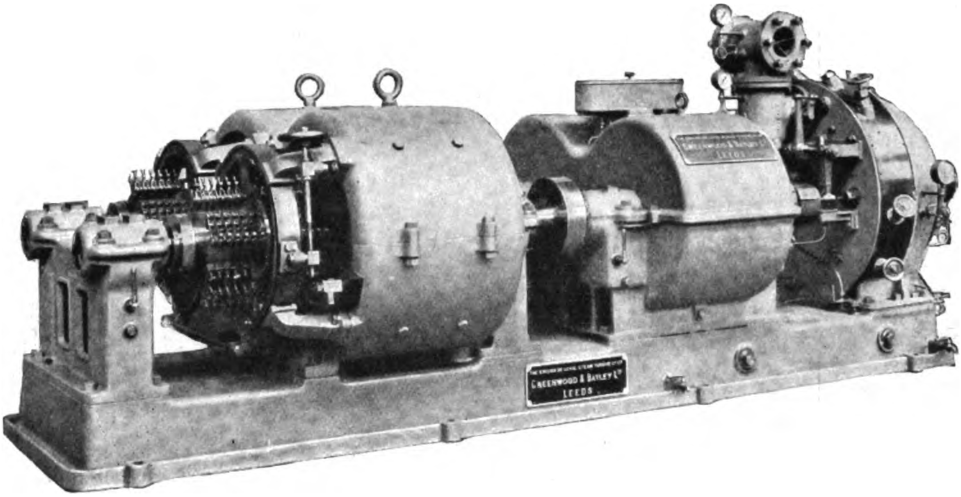


FIG. 422.—DE LAVAL STEAM TURBINE COUPLED TO TWIN DYNAMOS OF 75 KILOWATTS EACH AT 1,000 REVOLUTIONS PER MINUTE, BY GREENWOOD AND BATLEY.

vided which suck air through the ducts and keep the commutator cool. The bars are mounted on a steel sleeve and held by steel rings shrunk over them, mica being placed over the sleeve and also under each ring. No **V** rings are used, the steel rings being sufficient to hold the bars rigidly. The fans are cased in by a perforated casing seen clearly in the illustration. The overall length of the commutator is approximately five feet. Four of the compartments are used for collecting current, while the central one is left to provide additional cooling surface (*vide supra*). The makers find that this type of commutator runs perfectly with an inappreciable wear on the brushes, and maintains its surface in excellent condition without special attention. Sparkless collection with fixed brush position, and even with overloads of the order of 75 per cent., is obtained, there being four commutating poles placed between the four main poles. The main poles are laminated, and the main yoke cast steel. The commutating poles are provided with an entirely distinct (except for the air gaps) magnetic circuit; they are of laminated iron supported by two laminated circular yokes, of which one is placed on each side of the main yoke. A slotted drum armature is used having no binding wires, but having the coils fixed with wedges which engage with grooves in the slots and the end windings held in by flat steel bands and manganese bronze covers.

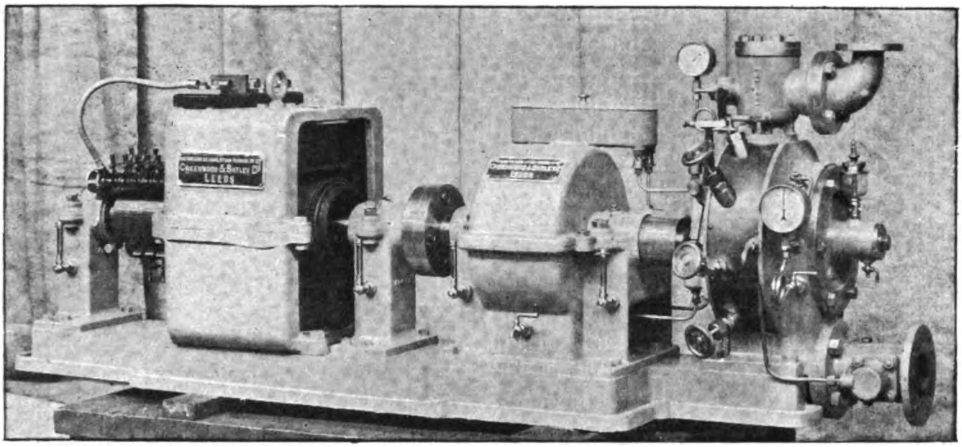


FIG. 423.—20 KILOWATT BIPOLAR DYNAMO AT 2,000 REVOLUTIONS PER MINUTE COUPLED TO DE LAVAL STEAM TURBINE.

ELECTROLYTIC DYNAMOS.

There is a considerable demand for very low voltage dynamos for electrolytic work, and the demand is rapidly increasing owing to the great extension of the electro-chemical industries.

Until the last ten or fifteen years very low voltage dynamos were only required for electroplating work, and this did not necessitate dynamos of any size. A small machine for 600 amperes at 5 volts by Messrs. Crompton and Co., is shown in Fig. 425, the speed being 1,000 revolutions per minute.

This is a bipolar machine with single copper brushes, and their enormous size, relative to the whole machine, will be noticed.

The commutator is 5 in. in diameter, with eighteen segments, the width of each

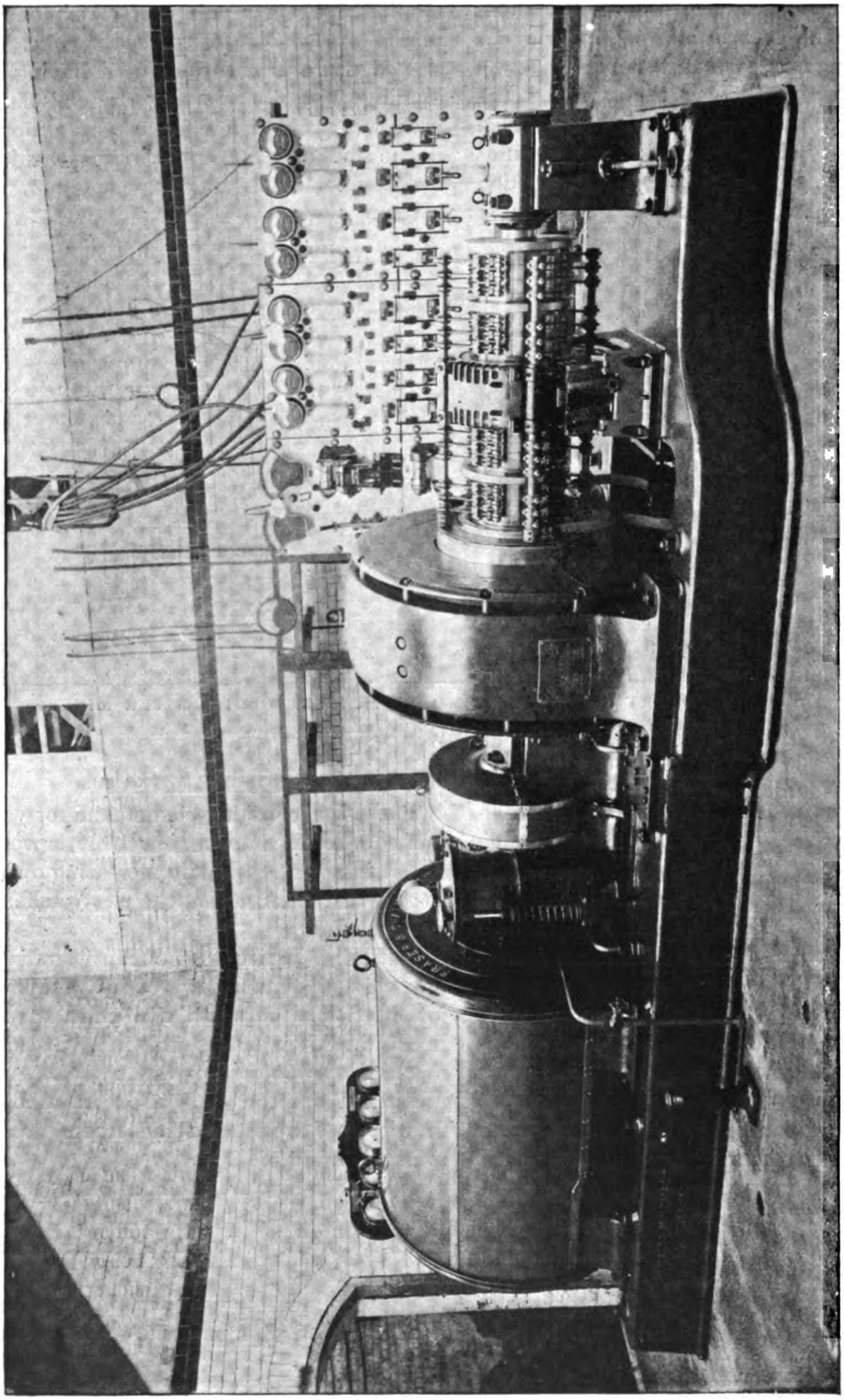


FIG. 424.—FOUR POLE, 450 KILOWATT GENERATOR, BY SIEMENS BROTHERS, WITH COMMUTATING POLES, DIRECT COUPLED TO A RATEAU EXHAUST STEAM TURBINE, BY FRASER AND CHALMERS, RUNNING AT 1,500 REVOLUTIONS PER MINUTE.

bar being ·813 in., tapering to ·411 in., at the bottom.

The brushes cover two segments of the commutator, and are 2½ in. wide by $\frac{15}{16}$ in. thick, giving a current density through the section of the brush of about 250 amperes per square in.

Carbon brushes would be, of course, quite out of the question for a machine of this kind, as we should at once lose in heat at the brushes about 2 × 600 = 1,200 watts, or two-fifths of the whole output ! And a commutator to dissipate this amount of heat would, at 2½ watts per square in., have to present a radiating surface of 480 square in. which for 5 in. diameter would give a length of over 30 in.

One of the most important electro-chemical industries is copper refining, for practically all the copper used to-day is refined electrolytically. A Westinghouse dynamo for copper refining is shown in Figs. 426 and 427. The output is 360 kilowatts at 250 revolutions per minute at 90 volts, the current thus being 4,000 amperes. There are twelve poles. The armature has a double or "duplex" winding, each half being complete in itself and independent of the other, of which it is an exact counterpart. This enables the output to be taken from two independent commutators, one at each end of the machine, and connected each to one half of the duplex winding.

Carbon brushes are used in this case to effect the collection of current. It will be noticed that the length of each commutator is considerably in excess of that of the armature core.

Each commutator has 60 brushes in 12 sets of 5 each, thus making 120 brushes for the whole machine. To have employed a single commutator of double the length would have introduced great difficulties, as not only would the mechanical question have presented difficulty owing to the very long segments (it would probably have been necessary with such a long commutator to shrink a steel ring round the middle of the commutator to counteract the centrifugal forces), but the cooling would not have been nearly so effective as with the double commutator, since when the length of a commutator becomes very great in proportion to its diameter, it is found in practice impossible to dissipate the same amount of heat per unit of area as is the case with a short commutator. This is very largely due to the great cooling effect of the commutator lugs, especially in a large machine such as this, running at a very high speed; if well designed, a perfect blast of air can be obtained through the commutator lugs, which has a considerable cooling action on the commutator, since the heat conductivity of copper is very great.

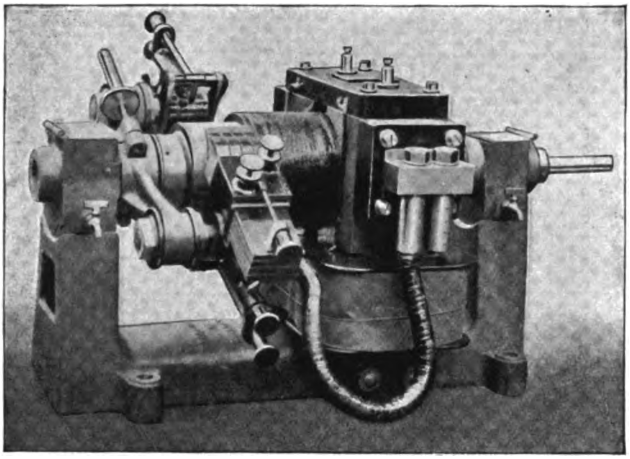


FIG. 425.—DYNAMO FOR ELECTROLYTIC WORK GIVING 600 AMPERES AT 5 VOLTS.

HOMOPOLAR DYNAMOS.

There is a small but interesting class of dynamo, of which Faraday's disc, described on page 419, is the prototype. In this class of machine the moving conductor becomes the seat of a unidirectional instead of an alternating E.M.F. owing to the fact that it suffers no reversal of magnetism. The type is hence described as acyclic or homopolar. Machines built on this principle are invariably (with the exception of one described below) of low voltage, but may be readily built for exceptionally large currents. Their chief merit is extreme simplicity of construction, resulting mainly from the absence of windings on the rotating portion. They may be suitably employed for electrolytic work, and at ordinary speeds are of little use for anything else. Designs have been made for higher voltages, however, and a machine was recently built and used in America, and described before the American Institution of Electrical Engineers by Mr. J. E. Noeggerath. An abstract of this paper appeared in the *Electrical Review* of London,* and this abstract is, by courtesy of the publishers, quoted *in extenso*:—

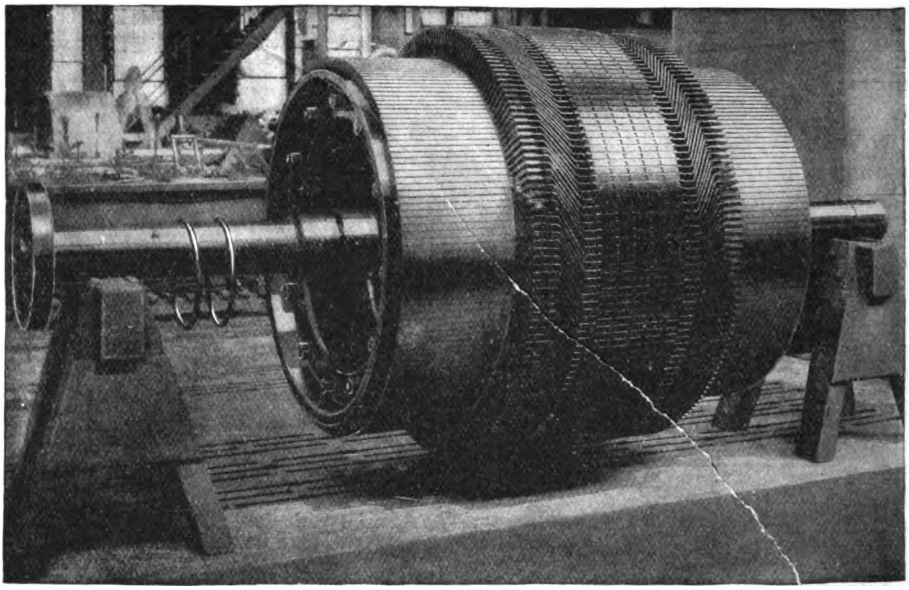


FIG. 426.—DOUBLE-COMMUTATOR DOUBLE-WOUND ARMATURE FOR ELECTROLYTIC WORK.

The author pointed out that acyclic generators could be classed mainly under two heads—the radial and the axial types—according to the position of the armature conductors. Various forms are shown in the Figs. 428 to 431, the positions of the brushes being indicated diagrammatically. Fig. 432 represents the type dealt with in the paper, the armature consisting of a solid cast-steel cylinder, carrying on its surface a small number of conductors connected at both ends to ts of collector rings. The field is of cast-st with co-axial field coils, as shown in the figure. There are two sets of brushes, which access is gained through openings the frame, and the brushes are connected series by means of stationary conductors

---

* February 10, 1905.

The course of the magnetic flux is shown in Fig. 432 by dotted lines; the E.M.F. generated in each armature conductor is constant in magnitude and direction, the field being uniform, and the total E.M.F. is given by—

$$\therefore E = 1{\cdot}66\, \phi\, N\, n\, 10^{-10},$$

where ϕ = total flux, N = revolutions per minute, and n = number of armature conductors in series.

Fig. 433 is a section of the machine at right angles to the axis in the plane of the brushes, showing the direction of the field by radial lines.

Fig. 434 represents the simplest form of circuit in a machine of this kind; C is one of the armature conductors, R one of the stationary or frame conductors, and C_r, B, the collector rings and brushes. The reactions set up by the currents flowing in this system are of two kinds—those due to the straight conductors, and those due to the rings. The latter are of especial interest and importance.

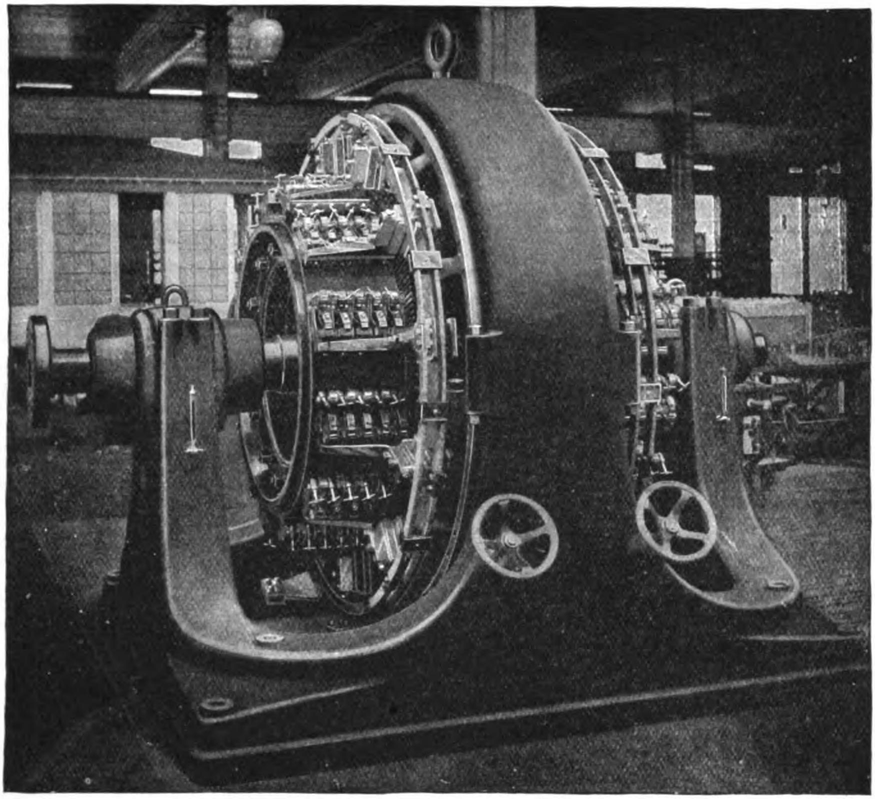


FIG. 427.—LARGE DYNAMO FOR ELECTROLYTIC WORK, WITH TWO COMMUTATORS. OUTPUT 4,000 AMPERES AT 90 VOLTS AND 250 REVOLUTIONS PER MINUTE.

It will be seen that currents flow in the left-hand ring both ways from P_1 to B_1, inversely proportional to the resistances of the two paths, which are continually varying in length, and these currents give rise to magnetic fluxes in the solid steel by which they are surrounded. The variation in magnitude and direction of the resulting magnetisation is necessarily accompanied by hysteresis and eddy currents in the steel, and also weakens the main field. It could be done away with by placing brushes all round each ring, but this is not a practical solution of the problem. The difficulty has been completely overcome by making the connections (P_1, P_2, etc.) between the armature conductors and the rings (R_1, R_2, etc.) follow a spiral of one complete turn, while the brushes (B_1, B_2, etc.) follow a spiral of one or more turns in the opposite direction.

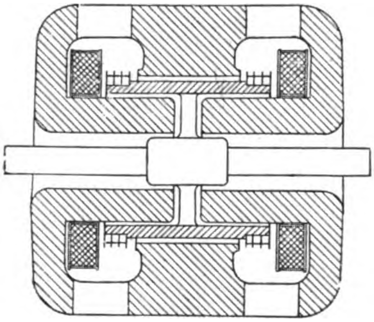


FIG. 428.

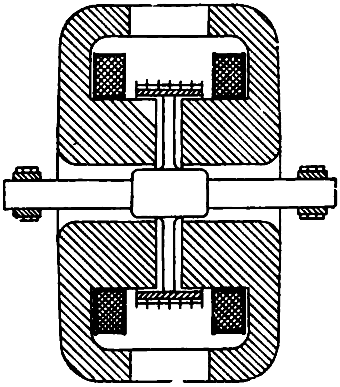


FIG. 429.

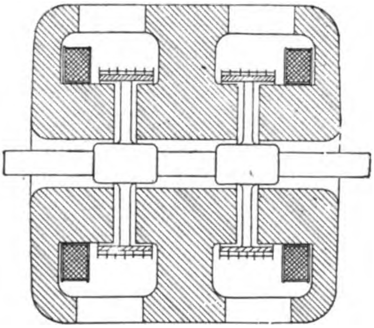


FIG. 430.

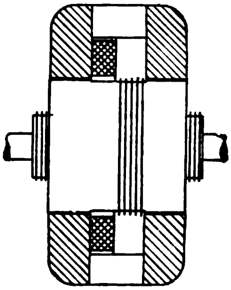


FIG. 431.

TYPES OF HOMOPOLAR DYNAMOS.

The currents in the straight conductors, C, set up secondary fluxes, indicated by the curved lines in Fig. 433, which pass through the frame as the armature revolves and give rise to losses, besides, on the whole, weakening the main field. By placing the conductors close together, or preferably by using broad, flat conductors closely opposed, the radial components of these fields are neutralised. The resultant secondary field, indicated at B, Fig. 433, is circular, at right-angles to the main field, tending to increase the path of the main flux, and, on the whole, to weaken it. When the armature and frame conductors are kept close together, as at A, Fig. 436, the reaction is insignificant; but when the space between them is filled with steel, as at B or C, Fig. 436, the reaction is appreciable, but can be kept low.

Various ways of compound winding are available. The connections between the stationary conductors and the brushes, for example, may be arranged as in Fig. 437 so that the currents in them assist or oppose the field currents, and then, by shifting the brushes, it is obviously possible to vary the E.M.F. at will and to adjust the compounding ; or the armature conductors may be shaped, as in Fig. 437B, to give a fixed compounding. It follows that series generators and motors can be built without field coils, and if the arrangement of Fig. 437A is used, the direction and magnitude of the E.M.F. of a generator can be controlled by shifting the brushes, while the speed, torque and direction of rotation of a motor can similarly be varied. Fig. 438 shows how easily the generator can be used on a three-wire system.

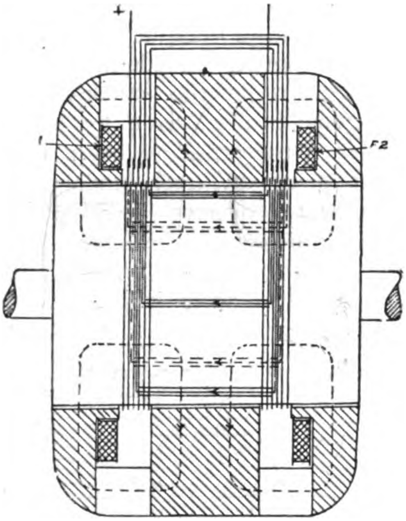


FIG. 432.—TYPE OF MACHINE USED FOR LARGE OUTPUT.

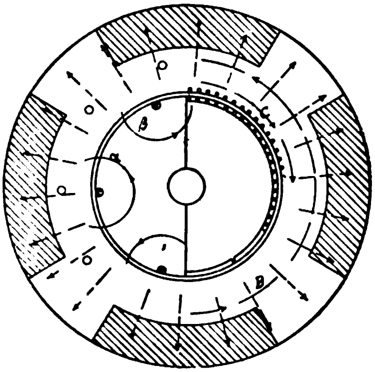


FIG. 433.—CROSS-SECTION OF MACHINE SHOWN IN FIG. 432

The design of a radial type of acyclic generator is generally similar to that of the axial type, with suitable modifications.

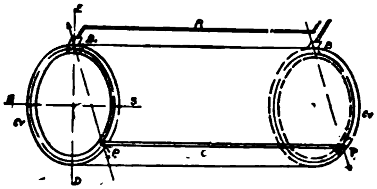


FIG. 434.—SIMPLE CIRCUIT IN MACHINE OF TYPE SEEN IN FIG. 432.

The efficiency of the machines is about the same as that of a turbine-driven commutating dynamo, but the C^2R losses in field and armature are small, as also are the hysteresis and eddy losses, provided that the fields (including leakage fields) are all uniformly distributed round the circumference of the armature. The principal losses are due to friction and pressure drop at the brushes.

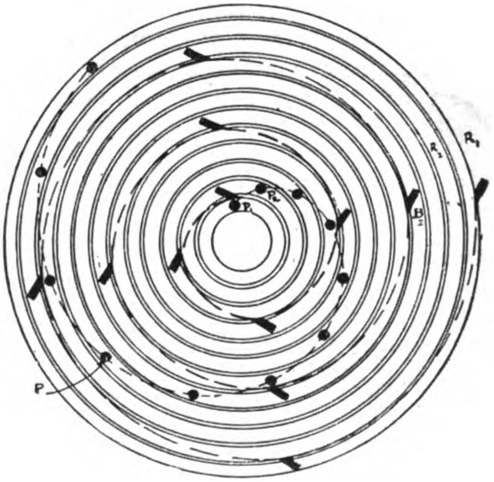


FIG. 435.—CONNECTIONS BETWEEN BARS AND RINGS TO MINIMISE MAGNETIC REACTIONS.

The variation of the losses and the temperature of the ring with speed is shown in Fig. 439, and the variation of the pressure drop with current density in Fig. 440. Some resemblance between the behaviour of the rubbing contacts at high speeds and that of the electric arc is traced; for example, it often happens that pressures 10 or 20 times the normal are required to start the flow of current. Increase of pressure on the brushes has little effect on the drop; but high pressures are necessary on account of a tendency to sparking at high speeds and current densities.

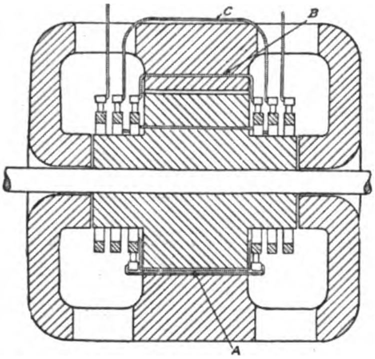
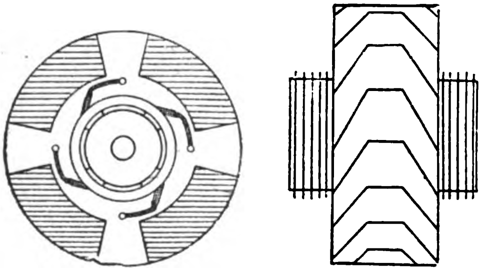


FIG. 436. — ARRANGEMENT OF STRAIGHT CONDUCTORS TO MINIMISE MAGNETIC REACTIONS.



A B

FIG. 437.—ARRANGEMENTS TO COMPOUND HOMOPOLAR MACHINES: A, BY STATIONARY CONNECTORS; B, BY ARMATURE CONDUCTORS.

In the case of the 300-kilowatt 500-volt turbo-generator which has been tested, the full-load losses, without windage and bearing friction, were 28 kilowatts. The efficiency curve, Fig. 441, is remarkably flat, and the regulation is 6 to 12 per cent. The armature and frame are of cast-steel, the former having 24 conductors[*]—flat sheets, bent to fit the smooth surface. The conductors are driven by lugs projecting from the armature body, and are held in place by steel binding wires. There are 12 collector rings at either end of the armature, assembled close together and mounted on a shell, and 24 brushes, to which access is gained through eight openings in the frame. The total weight of the machine is about the same as that of the ordinary type, but the very low copper weight and simple construction of the acyclic type and the absence of commutation troubles are in favour of the latter.

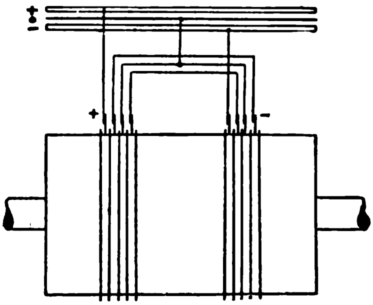


FIG. 438.—CONNECTIONS FOR THREE-WIRE CIRCUIT.

SHUNT REGULATION FOR DYNAMOS.

For all dynamos, except the very smallest compound machine, a shunt regulator is necessary. A shunt, or field, regulator consists of a variable resistance inserted in the circuit of the shunt winding for the purpose of adjusting the current in it. For a shunt machine a field regulator is absolutely requisite, as there will be a very considerable difference in the necessary field

[*] Elsewhere it is stated that there are 12 armature conductors and 12 frame conductors in series.

strength to maintain constant voltage from no-load to full-load, to compensate for the C R drop in the armature, the drop at the brushes, and the demagnetising effect of the armature ampere turns.

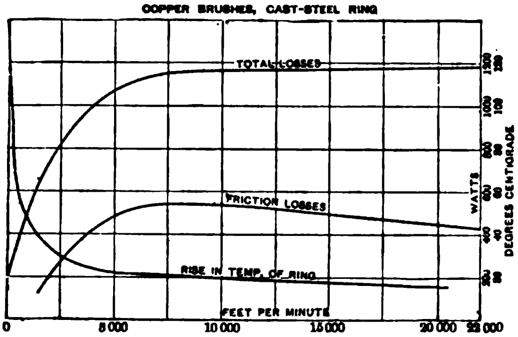


FIG. 439.—CURVES CONNECTING LOSSES AND TEMPERATURE WITH SPEED.

We can tabulate the functions of the shunt regulator for shunt and compound dynamos as follows :—

In *shunt dynamos*, to compensate for :

(*a*) The armature reaction ;

(*b*) The C R drop in the armature ;

(*c*) The C R drop in the brushes ;

(*d*) The increase of resistance of the field and armature windings as the machine heats up.

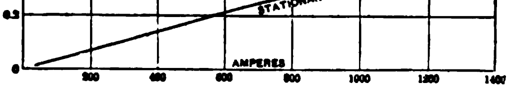


FIG. 440.—CURVES CONNECTING VOLTAGE DROP WITH CURRENT DENSITY.

In *compound dynamos*, to compensate for :

(*a*) The increase in resistance of the shunt field winding as the machine heats up, and to a small extent the increase in the resistance of the armature and compound winding.

In practice, when the calculation for the field winding is made, a margin is always intentionally left, that is, the shunt is designed to provide, if wanted, about 10 per cent. more ampere turns than calculation gives as needed, so that if for any reason due to the unavoidable small variations in manufacture, such as loose winding of the field coils (giving a greater mean turn for the coil than expected), or a possible inaccuracy in the air gap, or a variation in the quality of the iron or cast steel employed, and such causes, it may not be necessary to re-wind the field coils. The margin is provided by making the winding of lower resistance than the calculated value, so providing a higher current at the voltage employed. The field regulator operates by absorbing more or less voltage, and so reducing the current in the field winding to the desired value found by the test. If the excitation on test comes out exactly as expected, the shunt regulator will then take up the whole of the margin left, without detriment to the running of the machine. The construction of field regulators is dealt with in Section IX. on switch gear.

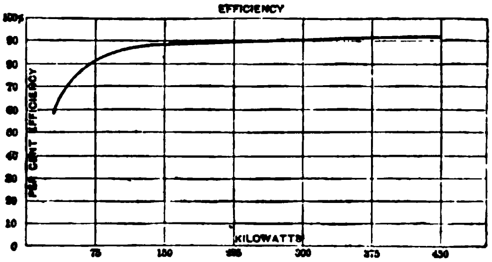


FIG. 441.—EFFICIENCY CURVE OF 300 KILOWATT 500 VOLT MACHINE.

CONTINUOUS-CURRENT MOTORS.

There is intrinsically no difference between a machine which is to be used as a motor or as a dynamo, but practically there is often a wide divergence in mechanical form, to better meet the, in many cases, widely different conditions of operation of the two classes of machine.

For small machines, however, most makers nowadays will supply an identical machine for either dynamo or motor work, in the standard semi-enclosed or protected type, up to about 50 horse-power or 40 kilowatts, and beyond this, if the machine is of the standard type, the manufacturers often arrange their machines to be of the open type for dynamos and the semi-enclosed type for motors, though in every other detail the machines may be the same. A motor is generally, of course, placed in a more exposed position, is more likely to be tampered with, and receives less attention than the corresponding dynamo; hence the necessity for more protection of the commutator and other parts.

As regards field windings, shunt, series and compound windings are used; but, in the case of motors, the series wound machines find very wide application, quite contrary to the case with dynamos, where, as we have seen, series windings for the field have only a very restricted use. The shunt motor is, for ordinary driving purposes, preferable where no great starting effort is required. A well-designed shunt motor will have quite a small speed drop from no-load to full-load, from 5 to 8 per cent. in the smallest motor down to 2 to 3 per cent. for the largest shunt machines. The compound wound motor is only in limited use, and of the two types of compound wound motors—the "cumulatively" and "differentially" wound—the former is preferable, though the latter operates at a more constant speed with varying load.

In the cumulatively compounded motor a series coil is used, which acts magnetically with the shunt winding, and, by greatly strengthening the field at starting, gives a high starting torque; but such a motor will, of course, have a very bad speed regulation, the field being always strengthened when the load comes on, resulting in a considerable drop in speed.

The differentially compounded motor with series coil acting magnetically in opposition to the shunt winding, possesses a rather low starting torque, unless special switch gear is used to short circuit the series winding at starting. The cumulatively compounded motor is often conveniently replaced by the simple series motor, which possesses the same characteristics, but to a greater degree. This type, however, is very useful in those cases where a motor is required for belt-driving and to possess at the same time the characteristic features of the series motor, high starting torque and constant rapid acceleration. A plain series motor would not be permissible in this case, as if the belt were thrown, the series motor would overrun and soon damage itself, due to the excessive speed; whereas, if the field is maintained to some extent by a shunt coil, this would not occur. We shall describe a cumulatively compounded motor by Messrs. Laurence Scott and Co., Limited, in which this falling speed characteristic with load is taken advantage of in a special printing press motor, where it is advantageous.

A small standard bipolar motor by Messrs. Johnson and Phillips, Limited, is shown in Fig. 442, in two sectional views. This is rated in the makers' list at 3 horse-power at 1,000 revolutions per minute, and 2 horse-power at 850 revolutions per minute, the machine being standardised for 110 and 220 volts. Motors of such small output are rarely required above 220 to 250 volts, as, up to 3 or 4 horse power, most of the supply companies permit motors to be placed across the middle and one of the outers of the usual three-wire network; but above this size they

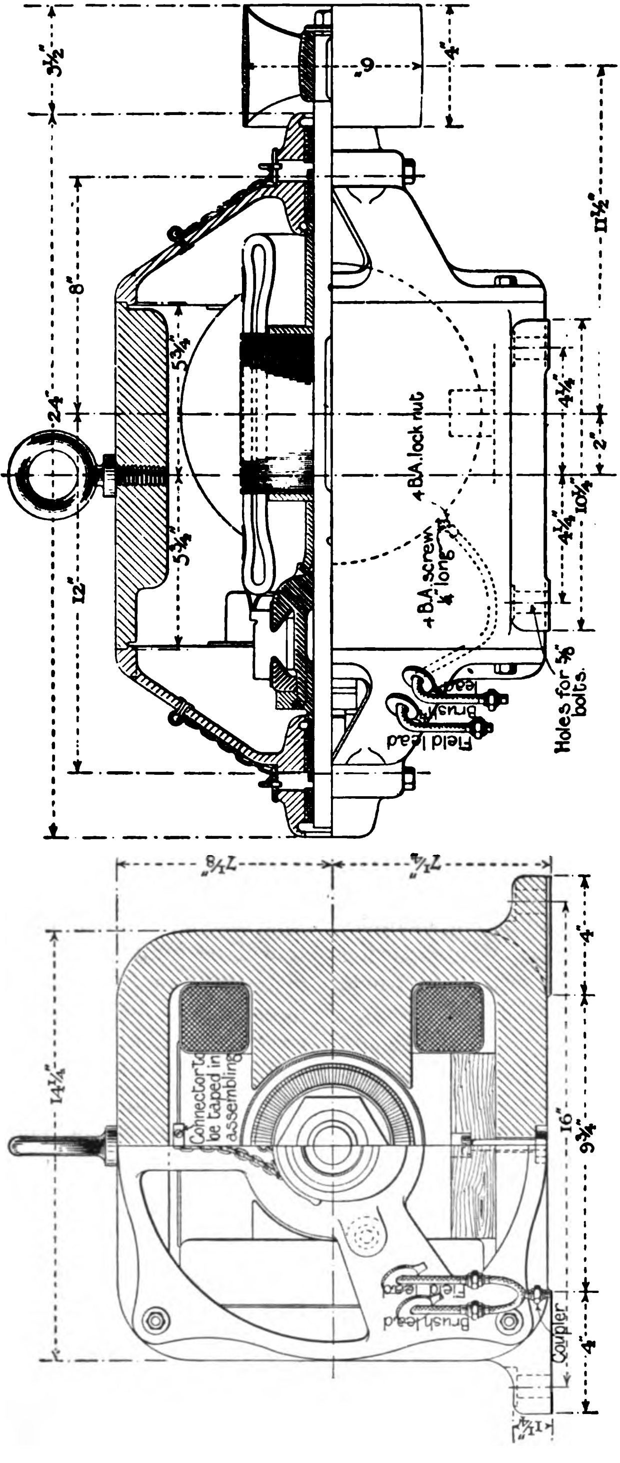


FIG. 442.—SMALL BIPOLAR MOTOR BY JOHNSON AND PHILLIPS, 3 HORSE-POWER AT 1,000 REVOLUTIONS PER MINUTE.

require motors to be placed across the outers, and consequently they must be wound for 440 to 500 volts.

This little machine is of very simple construction, the yoke and poles being in cast iron in one piece, and no pole tips are fitted; the use of cast iron in the pole cores, of course, means more field copper, owing to the larger section of cast iron required compared with cast steel or wrought iron to carry a given magnetic flux; but to offset this, there is a considerable saving in labour, and consequently on the whole, the design comes out cheaper.

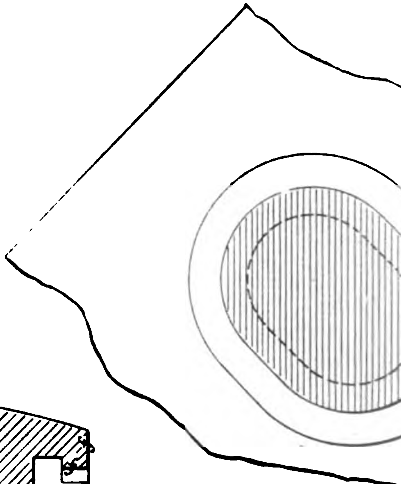
The armature is of substantial construction, and the commutator is of very large diameter; there is no brush rocker, the brushes being permanently fixed in the neutral position, brush spindles being carried by the end cover. There are several novel features to be noted: first the fan blade pulley which, when the machine is at work, drives a good current of air into the machine, ensuring very cool running; and next the neat arrangement for connecting up the motor to the supply. There are no terminals fixed on the machine itself; instead, cables are brought through bushed holes in the end cover, and these cables terminate in screwed couplings, which, by means of right and left handed screws, quickly make a sound connection.

The Rhodes Electrical Manufacturing Company, Ltd., manufacture a four-pole semi-enclosed motor. Laminated pole tips and bolted-on poles are used, and the end covers are held by means of long bolts passing right through the machine. The brush rocker is very massive, there being only two spindles, though the machine is four-pole; but this is, of course, quite permissible with a two-circuit series winding. Details of the commutator and brush gear, and also of the bearings, are shown in Figs. 443 and 444.

A Johnson and Phillips four-pole motor, rated at 50 horse power, at the highest speed quoted of 950 revolutions per minute, and 15 horse power at the lowest, 350 revolutions per minute, is shown in Plate IV. As complete dimensions are given, we are able to deduce the value of the output coefficient for this particular machine. Taking the equivalent kilowatt output as 40 kilowatts at the high speed, and 12 kilowatts at the lowest speed, we find that the values come to C = ·026 at 950 revolutions per minute, and ·022 at the lowest speed, the coefficient being higher at the top speed owing to the heating limit causing a reduction in the output at the low speed. A comparison with our curve for the value of this coefficient is interesting.

The diameter of the armature, as will be seen from the detail drawing, Plate V., is 13 inches, and the gross core length 9¼ inches. The makers list a 13 in. × 6 in. machine, and it is therefore evident that this line of standard machines is made in two armature lengths for each diameter, which is a plan often adopted, as the same core discs, standard commutator segments, brush gear, and so forth can then be used for the two sizes. The yoke is of cast iron, with cast steel poles of oval section *cast in*, and for the shorter machines in each diameter *round* poles are employed. It will be noticed that the armature end plates are of a rather curious shape; this is in order that they may also form supports for the end bends of the armature. This motor has wire grids of coarse mesh over all openings in the case to afford protection, whilst at the same time allowing of free ventilation, and ample ventilation is ensured through the armature core by means of three ventilating ducts.

For these machines two sizes of commutator are shown, one in section and the other in elevation, these being the two standard commutator lengths per 220 and 440 volts, according to requirements;



Section through

These
to be or
sides of

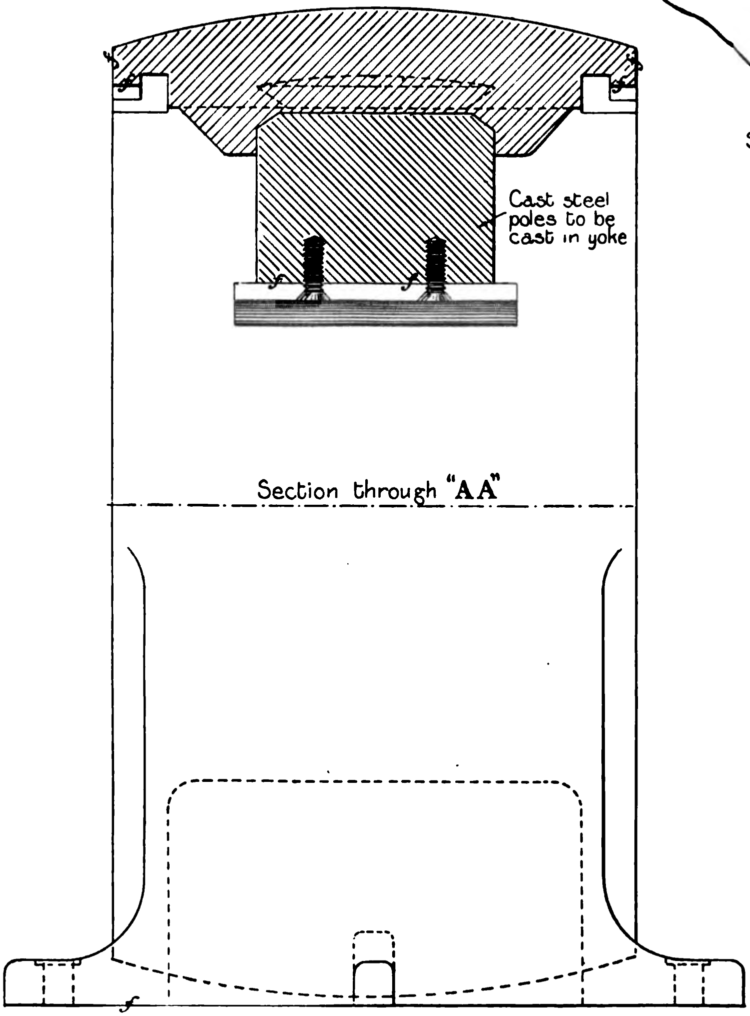
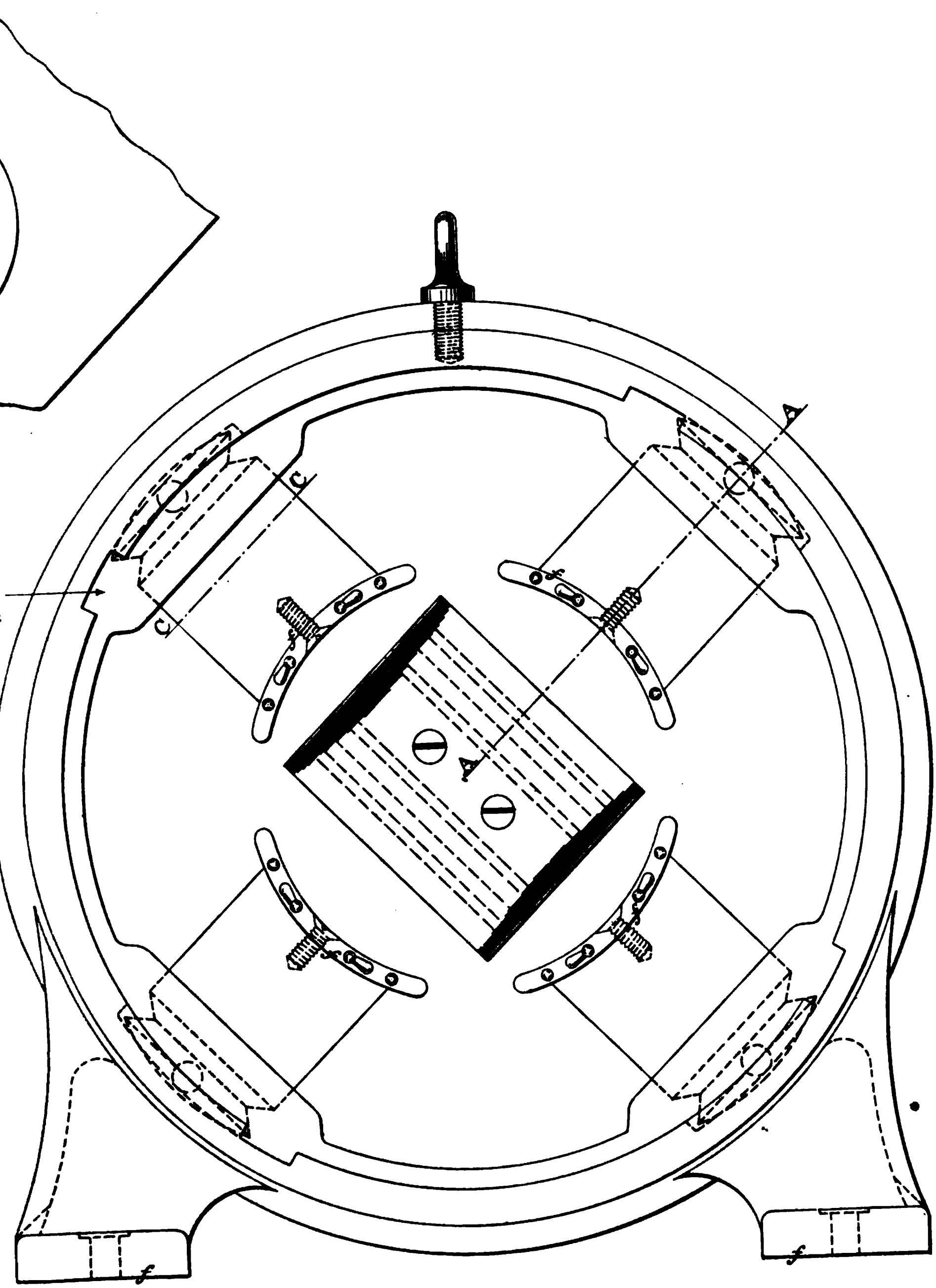
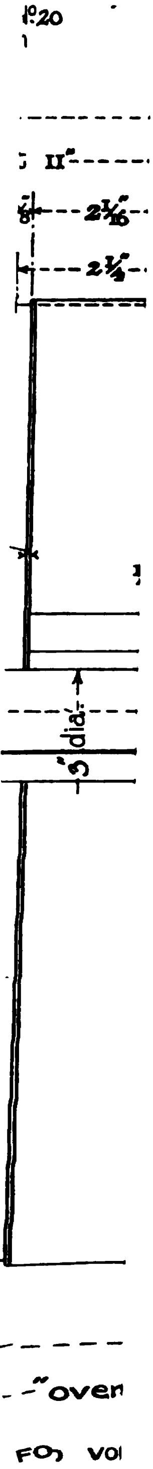


PLATE IV.—CARCASE AND POLE CONSTRUCTION OF JOHNSON



ND PHILLIPS 50-H.P 950 R.P.M. 4-POLE MOTOR. (*See page* 490.)


1:20
II"
2 1/16"
2 1/4"
3" dia.
"over
FO VO

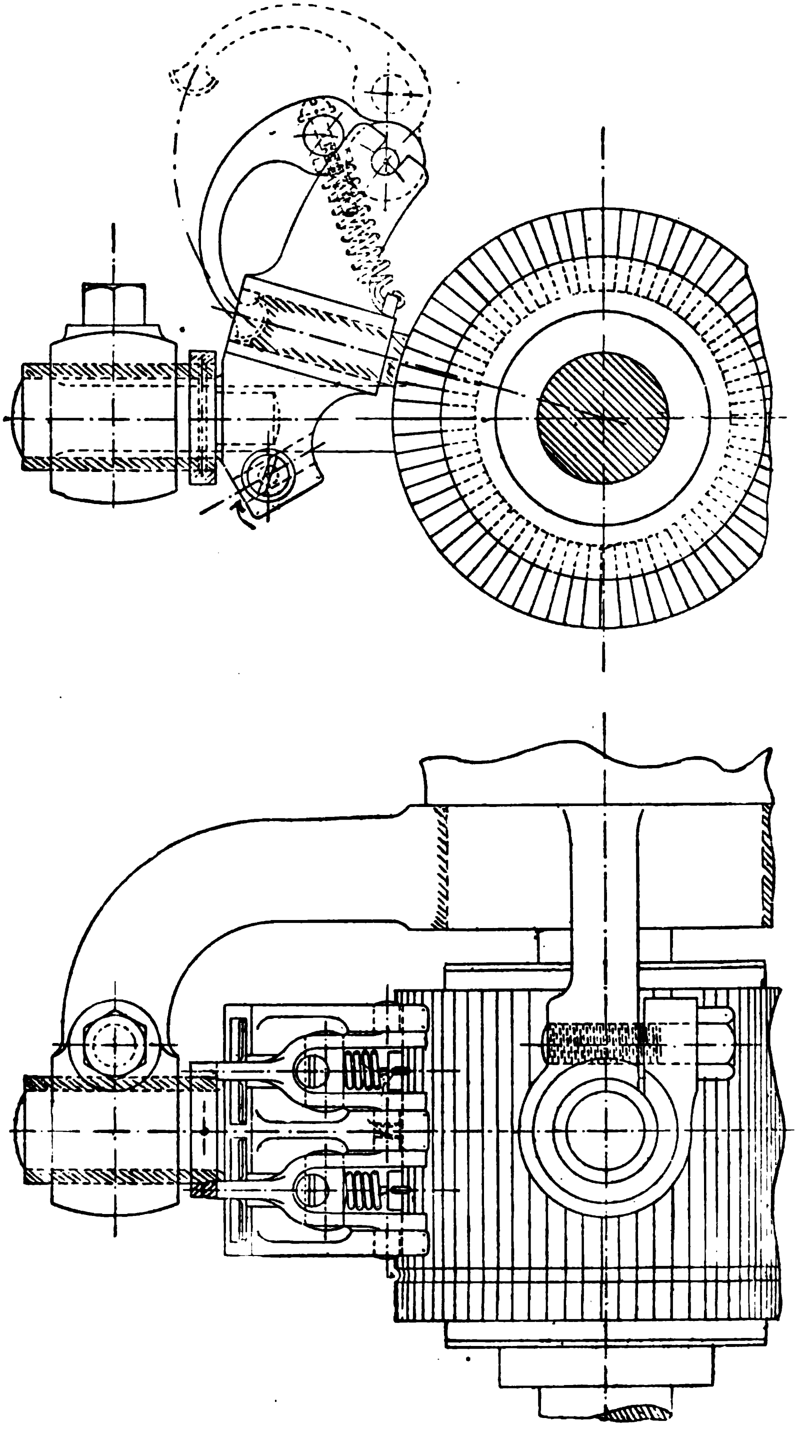


FIG. 443.—COMMUTATOR AND BRUSH GEAR OF SMALL FOUR-POLE SEMI-ENCLOSED MOTOR BY RHODES MANUFACTURING COMPANY.

but no other difference is made in the design. When the short commutator is employed, as is shown in the general sectional view of the armature, the commutator lugs are brought down sloping whilst with the long commutator the lugs would be brought down to the commutator vertically.

The bearings are of the swivel, self-oiling type, with two oil rings to each bearing.

There are three ventilating ducts and provision for four armature binding bands along the core, and the armature plates, instead of being threaded direct on to the shaft, as in the usual construction for machines of this size, are threaded on to a cast iron sleeve which extends the whole length of the shaft, thus strengthening the shaft very considerably, and allowing a shaft to be replaced without interfering with the armature proper.

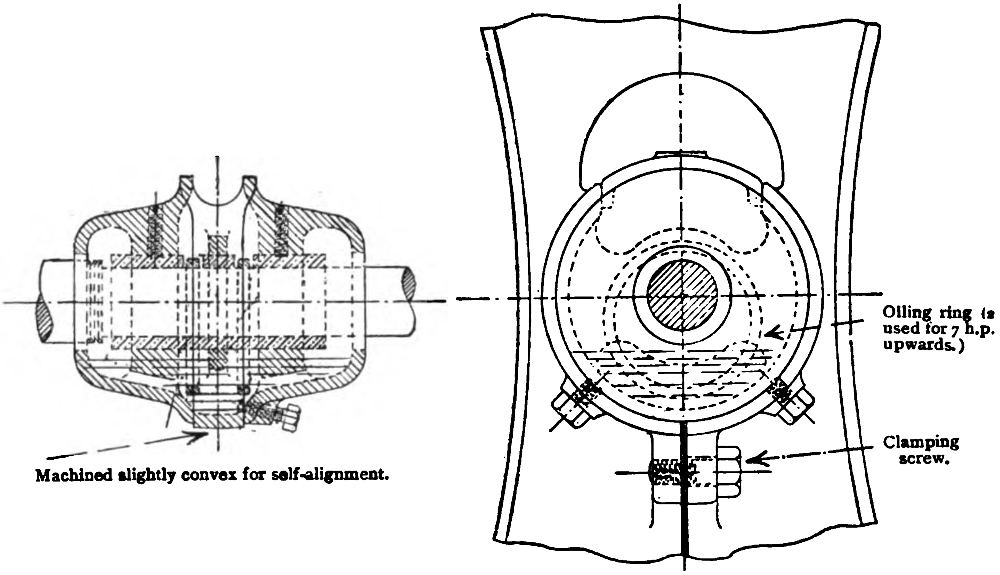

Machined slightly convex for self-alignment.
Oiling ring (2 used for 7 h.p. upwards.)
Clamping screw.

FIG. 444.—DETAILS OF BEARING OF RHODES MANUFACTURING COMPANY'S SMALL SIZE MOTORS. THE BEARING WILL DRAW OUT BY SLIGHTLY SLACKENING CLAMP SCREW.

A half-sectional view of a four pole semi-enclosed motor by the Lancashire Dynamo and Motor Company, Ltd., is shown in Fig. 445.

Access to the brushes is obtained through the large doors, a great convenience in this type of motor, in which accessibility to the brush gear is not always sufficiently studied. The field frame and poles are of cast steel, in one piece, and in the larger sizes of machine the yoke is divided, as in the machine we illustrate, facilitating inspection of the armature and erection. The pole cores are of oval section (as in the Johnson and Phillips motor we have just described), and laminated pole tips are bolted on.

Analysis of 20 horse-power variable-speed motor with commutating poles by Messrs. Laurence Scott & Co., Ltd., Norwich.

This is a standard semi-enclosed motor to give 20 horse power at 220 volts at any speed from 250 to 1,000 revolutions per minute by field regulation alone. Full drawings of this motor are shown in Plate VI., and performance curves in Figs. 446 and 447, and other data are given below.

Auxiliary commutating poles are fitted to meet the very special conditions of such a wide range of speed variation as 4:1 which is obtained in this motor.

Without such auxiliary poles, and with the sparking constants of this motor, only a moderate percentage speed variation would be possible with a fixed brush position, and this design illustrates very aptly a particular case in which commutating poles are of the greatest value.

The machine is of the four-pole type, the yoke and main poles being in a single steel casting, while the auxiliary poles are turned from round mild steel bar and bolted to the cast steel yoke; laminated

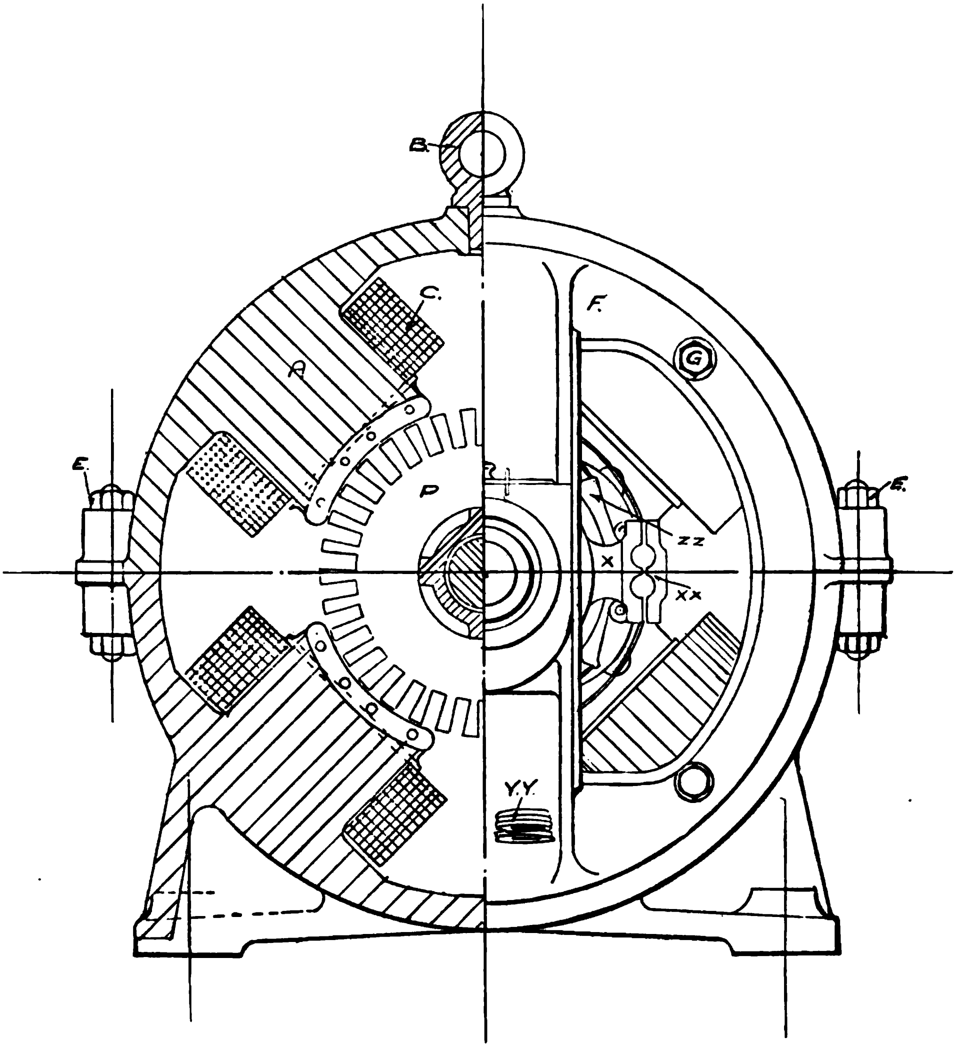


FIG. 445.—FOUR-POLE MOTOR BY LANCASHIRE DYNAMO COMPANY. A, POLE CORE; B, EYE BOLT; C, FIELD COIL; E, YOKE BOLTS; F, END SHIELD; P, ARMATURE CORE; X, BRUSH ROCKER; XX, CAP FOR DITTO; ZZ, BRUSH HOLDERS; YY, INSULATOR FOR TERMINAL.

pole tips are employed on the main poles, secured by set screws to the cores.

The armature core is built on a three-armed spider, a prolongation of which also serves as a commutator sleeve, and the armature core is efficiently ventilated by three radial ducts.

Performance curves are given in Figs. 446 and 447, these being the tested no-load saturation curve and the no-load loss curve at various speeds and constant excitation.

The principal dimensions and winding of this motor are as follows :—

Armature.

Outside diameter . . .	15 in.
Length of core (gross) . .	9 in.
Inside diameter core . .	7 in.
Number of ducts (¼ in. wide) .	3
Length of core (net) . .	7.75 in.
Number of slots . . .	53
Size „ .	1¼ in. × ·41 in.
Pole angle	57°
Number of commutator bars .	159
Diameter of commutator . .	14 in.
Number of spindles . . .	4
Brushes per spindle . .	3
Sizes of brushes . .	1 in. × ¾ in.

Field.

Main poles—	
Diameter of C.S. poles . .	7½ in.
Section C.S. yoke . . .	22 in.
Thickness of pole tip . .	1 1/32 in.
Dimensions of pole face	9 in. × 7·7 in.
Length of air-gap . . .	3/16 in.
Auxiliary poles—	
Diameter of W.I. poles . .	1¾ in.
Dimensions of W.I. pole face of auxiliary pole . .	1 in. × 5 in.
Length of pole core from yoke to end of tip . . .	7¾ in.

The armature has a two-circuit wave winding with two turns per commutator segment, and the total number of conductors in the armature is therefore 636. The armature conductors are laminated strip, there being eight strips 0·08 in. × 0·03 in. assembled into a bar 0·08 in. × 0·24 in., making a sectional area of 0·0182 square in. ; the current density is 2,120 amperes per square inch, the input into the armature being 76 amperes. The length of mean turn of the armature winding is 48 in., and the armature resistance at 140° F. is 0·166 ohms ; the volts lost in the armature are therefore $76 \times 0.166 = 12{\cdot}6$ volts and the C^2R loss is $(76)^2 \times 0{\cdot}166 = 960$ watts.

The field windings are as follows :—Shunt, 2,300 turns per pole of No. 16 S.W.G. single cotton-covered wire, the coils have a mean turn 31·5 in. long, and the resistance of four coils in series is 72 ohms. Auxiliary poles have 80 turns per pole of four No. 10 S.W.G. wires in parallel with a mean length of 12 in. and a total resistance for the four coils in series of 0·059 ohm at 140° F.

The excitation provided by the shunt winding is 7,000 ampere-turns per pole at full field, that is, at the lowest speed of 250 revolutions per minute.

This excitation generates an E.M.F. in the armature at 250 revolutions per minute of 200 volts, while the terminal volts are 220, the difference of 20 volts between the back E.M.F. in the armature and the applied voltage being absorbed by the drop in the armature, which, as we have already seen, is 12·6 volts and a drop of 2·5 volts at the brushes and 4·5 volts in the interpole winding at full load.

The winding on the auxiliary poles provides 6,000 ampere turns at full load, and these ampere turns will vary directly as the load of the machine, whatever the speed may be. The function of the auxiliary poles is to drive into the armature an amount of flux which will, under all permissible conditions of load and speed, generate in an armature coil, the current in which is being commuted, an E.M.F. equal and opposite to the reactance voltage generated in that coil. Now, it is obvious from inspection of the formula for the calculation of the reactance voltage given in Chapter II. that for any given machine, other things being equal, the reactance voltage increases proportionately with the load of the machine (the speed being constant) or proportional to the current input into the armature, or if the current into the armature be kept constant, the reactance voltage will increase proportionately to any increase in speed. If we make the assumption then (and it is practically sufficiently correct within the working limits of ioad of the machine) that the commutating field thus provided by the interpoles is proportional to the ampere turns in the interpole winding, it follows that the back E.M.F. induced in an armature coil by auxiliary pole flux will be proportional to the current in the windings of the interpoles, and hence with the load of the machine.

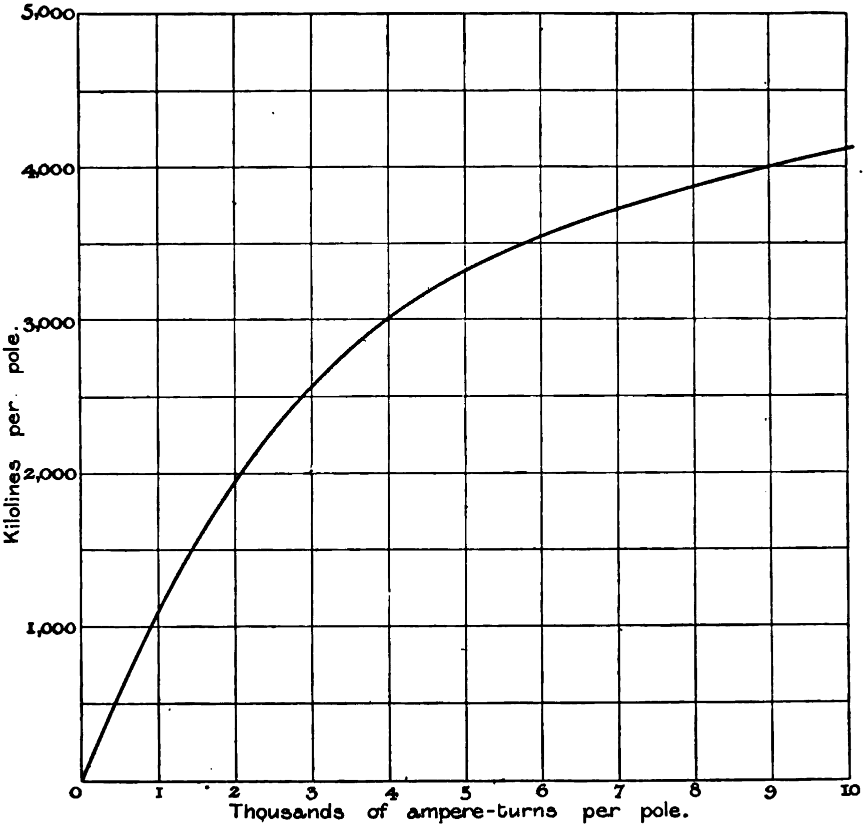


FIG. 446.—MAGNETISATION (OR "SATURATION") CURVE OF 20 HORSE-POWER MOTOR WITH COMMUTATING POLES BY LAURENCE SCOTT AND CO.

Thus the compensation will be correct at any load, and also at any speed, for though there is no increase in the auxiliary pole flux as the motor speed varies, yet the voltage induced will be greater as the speed becomes greater, and thus the employment of properly designed interpoles automatically at all loads and at all speeds provides a practically exact compensation for the reactance voltage.

To calculate the interpole dimensions and the necessary ampere turns required for the winding we proceed as follows :—

The ampere turns on the interpoles must be sufficient to both compensate for the reaction of the armature and to force the commutating flux across the air gap.

As the interpoles act between the main poles the full ampere-turns of the armature will be in opposition to the interpole field, and thus on the interpoles we must first provide a number of ampere turns per pole equivalent to the armature ampere turns per pole before we can force any auxiliary flux into the armature.

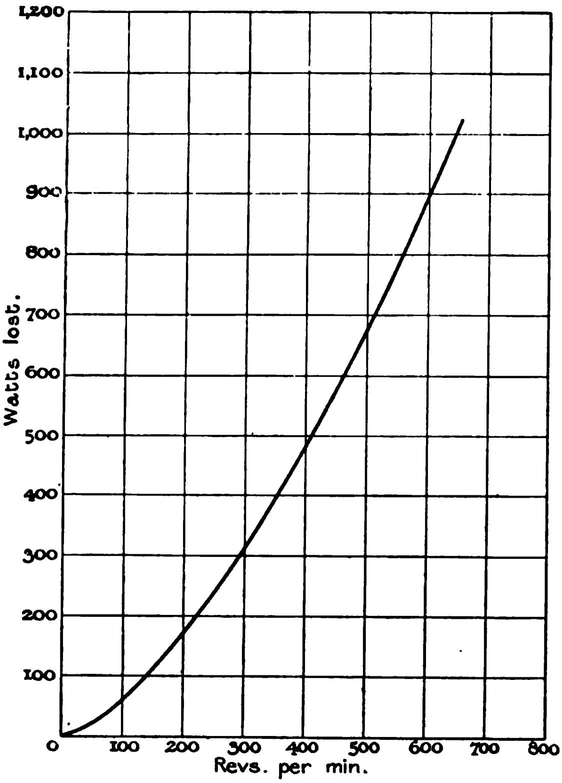


FIG. 447.—CORE LOSSES DUE TO IRON, WINDAGE, AND FRICTION IN MOTOR SHOWN IN PLATE III.

The armature ampere turns per pole on this motor are 3,000, and as the total ampere turns in the interpole winding are 6,000, we have after subtracting, still 3,000 ampere turns left in the interpoles for the purpose of forcing flux into the armature.

On working through a design for an interpole motor it is generally found that the total ampere-turns required on the interpole windings is from 1·5 times to twice the ampere turns required to overcome the armature reaction.

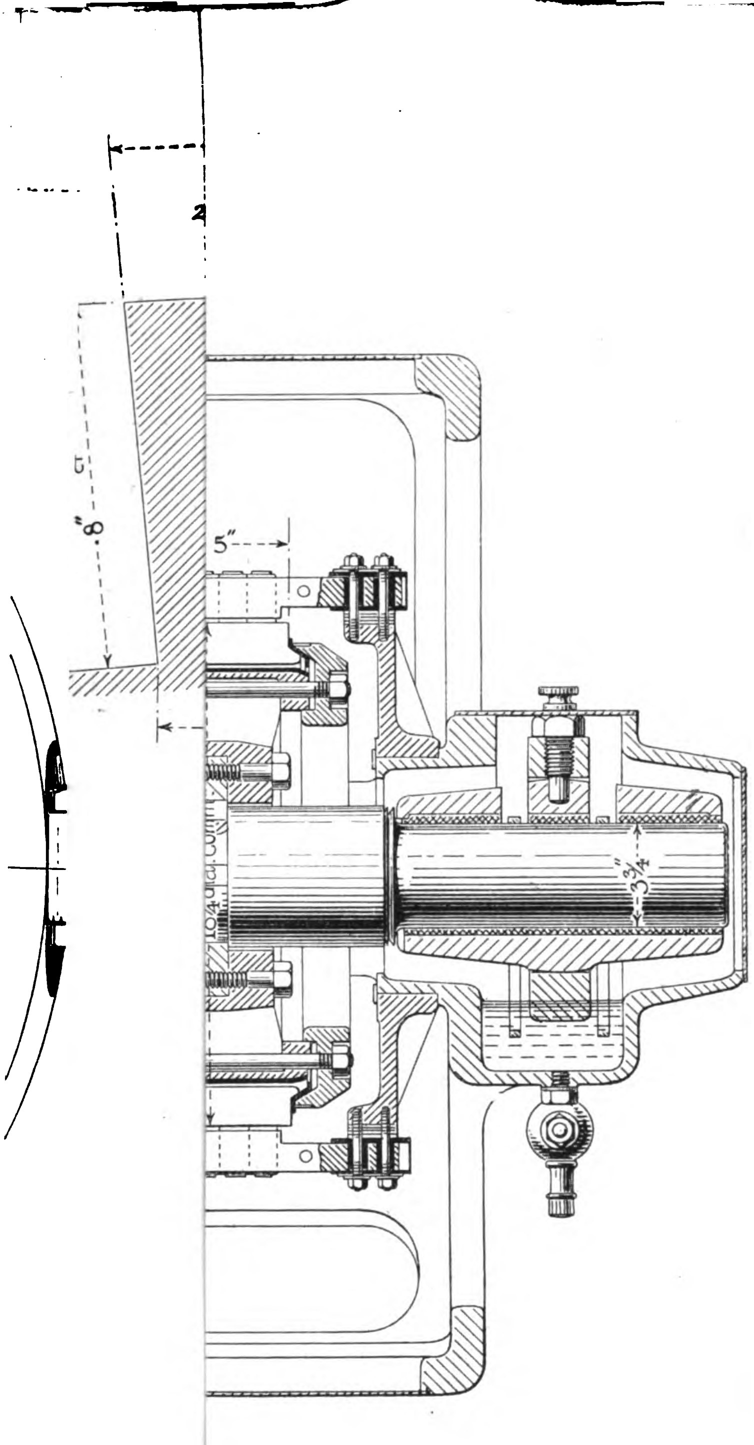
In Plate VII. and Figs. 448 and 449 we illustrate another example, in this case a printing press motor by the makers of the last example.

The speed curve of this machine more nearly resembles that of a series than that of a shunt motor; as series and shunt coils act together magnetically and at full starting current and normal voltage, the series ampere turns are over three times those provided by the shunt winding, but under normal full-load (top speed) conditions it is practically a shunt motor in its operation.

This design is an interesting contrast to the four-pole variable-speed shunt motor with commutating poles just described, the conditions in this case being such that considerable speed variation is obtained, but without resort to auxiliary poles to effect commutation. The duty is such that a heavy starting torque is required; when the motor has once started the torque falls to less than that required at full load, and the horse-power therefore increases more rapidly than the speed, and the maximum horse-power occurs only at top speed.

The principal dimensions are as follows:

ARMATURE.	
Outside diameter . . .	26 in.
Gross length of core . .	13 in.
Inside diameter core . .	14 in.
Number of ⅜ in. ducts. . .	3
Net length of core . . .	11·1 in.
Number of slots . . .	79
Size ,, . .	0·38 in. × 0·8 in.
Conductors per slot . . .	10
Size of conductors .	0·03 in. × 0·3 in.
Sectional area conductors	0·009 sq. in.
Turns per segment . .	1
FIELD.	
Pole angle	40°
Section of laminated poles	9 in. × 13 in.
Net sectional area . .	110 sq. in.
Net section of yoke .	55 sq. in.
Length of air gap . . .	$\frac{3}{16}$ in.


2
5"
8"
5
10¼ dia. comm
3¾"

t
a
6
a
p

Commutator.

Diameter	18 in.
Number of spindles	6
Brushes per spindle	4
Size of brushes	1 in. × ½ in.

The general construction of this motor is very similar to the six-pole generator by the same makers, of which we have given a detailed description and analysis.

The armature has a two-circuit wave winding, and a large number of commutator bars are used to give a low reactance voltage.

The output of the motor is 40 horse power at the top speed of 400 revolutions per minute, the intake being 88·5 amperes at 400 volts.

The series winding is arranged to carry 0·6 of the armature current when the armature current is 21 amperes, that is 12½ amperes, and under these conditions the temperature rise was 135° F. after 30 minutes, the current density being 3,000 amperes per square in., but under actual working conditions the current is never on the series coils so long as this.

By variation of the shunt field alone the speed can be varied from 160 with full field, up to 400 revolutions per minute, the top speed; when running continuously at the low speed the temperature rise on the shunt winding is 90° F. after six hours, but again, under service conditions, the motor is never worked at full field for this length of time, the guaranteed temperature rise being 70° F. after six hours at top speed to 10 per cent. over top speed.

For speeds under 160 revolutions per minute down to dead slow the series winding is put in circuit, and by virtue of the increased field provided, and also by reason of the very considerable voltage drop which occurs across the series winding, leading to a reduced voltage across the armature, very low speeds down to dead slow are obtained.

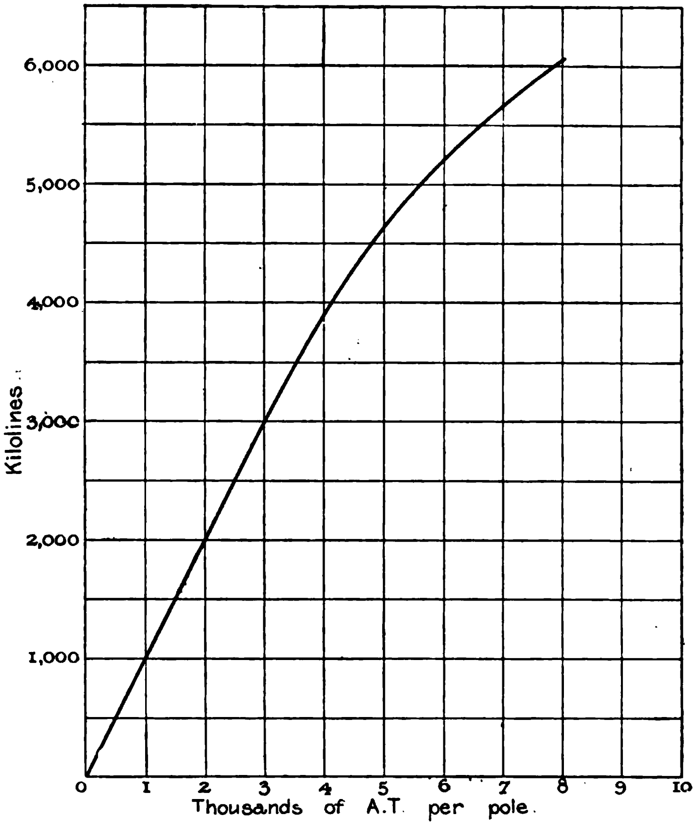


FIG. 448.—MAGNETISATION CURVE OF VARIABLE SPEED MOTOR BY LAURENCE SCOTT AND CO.

The series winding consists of 546 turns per pole of No. 14 S.W.G., having a total resistance for the six coils of 26·2 ohms at 100° F., and with 12½ amperes the voltage drop would therefore be 26·2 × 12½=326 volts.

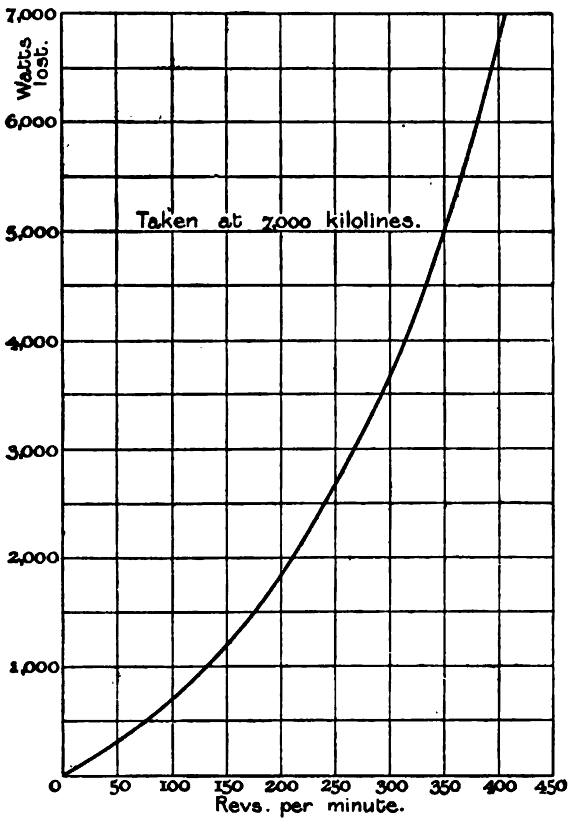


FIG. 449.—CORE AND FRICTION LOSSES IN VARIABLE SPEED MOTOR.

The shunt winding consists of 1,405 turns per pole of No. 17 S.W.G. wire, giving a total resistance at 100° F. of 137 ohms.

At full speed the armature C^2R losses are 4,200 watts, the core losses (with friction) 1,000 watts, the shunt loss 111 watts, and the brush loss 210 watts, the efficiency thus working out at 84 per cent.

Up to the present the motors we have illustrated have been of the semi-enclosed or protected type, with protective coverings over all openings in the frame, which, however, allow of free ventilation.

If a motor is *totally enclosed*, so that it is practically air-tight — and such motors are often required for use in the open, or in a dust-laden atmosphere—its rated horse-power for continuous service must be considerably reduced, owing to the absence of free ventilation, and the consequent rise of temperature which would follow heavy loading. A totally enclosed motor is only able to get rid of the heat generated by radiation from its containing case, whereas in the ventilated machine most of the heat is carried away by the air currents set up by the rotation of the armature.

A motor may be totally enclosed, and if it is only required to run for one or two hours continuously, will give its full output, as in this case it will not have time to attain to anything approaching its final temperature rise, owing to the heat liberated being absorbed by the various metal portions of the machine; the windings, commutator bars, and iron portions of the motor of course possess a consider able heat capacity. When, however, the motor has to run continuously, the temperature will continue to rise for from 6 to 12 hours, depending upon the size and other conditions, until the outside case attains such a temperature that it is able by radiation to dissipate continuously the whole of the energy which is being lost in the motor.

Owing to the considerable reduction in rating thus necessary for totally enclosed motors, a higher temperature is usually permitted than is the case with ventilated machines; otherwise the weight and cost become prohibitive. A temperature rise of 90° Fahr. for continuous running is the usual guarantee given for totally enclosed motors, and even then the rating has to be lowered.

The principal losses are, of course, the core and copper losses, and as the relative values of these losses depend upon the speed of the motor—the core losses being much higher in a high-speed machine than in the low-speed case, while the copper losses remain practically the same—it follows that a *greater* relative output will be obtained for a low-speed motor, when totally enclosed, than with a high-speed one, owing to the increased core losses in the latter case.

Actual tests on machines with known losses show that, taking the whole surface of the outside casing of the motor, from about 0·3 to 0·5 watts per square in. can be dissipated for a temperature rise of about 90° Fahr. inside the motor.

A totally enclosed motor for driving a windlass by means of worm gearing is shown in Fig. 450. This motor and windlass is by Messrs. Vickers, Sons and Maxim, Limited, and is of their standard type with sheet iron enclosing covers, the controller being mounted in a covered case on the top of the driving motor.

The terminals are also enclosed, and the whole machine rainproof.

An interesting construction followed by Messrs. Thos. Parker, Limited, under Rees' patent, is shown in Fig. 451. The construction enables repairs to be executed to the armature with great ease owing to the dividing of the magnet system across a horizontal line slightly above the diameter, and owing to the arrangement of bearings. The machine shown is a four-pole one with commutating poles, the top portion of the yoke being arranged to lift off two main poles and one auxiliary.

CRANE AND TRACTION MOTORS.

Continuous current motors have been applied very extensively for crane driving and for the purposes of electric traction; and for many years motors, especially designed for this kind of work, have been sold in great numbers. The enormous demand has resulted in almost complete standardisation as regards speed, voltage, and output, especially with the traction motors, greater elasticity being permitted in this respect for crane motors, owing to their more varied duties. The conditions under which both types of motors work are very similar, and in the case of traction motors, small bulk and standard external dimensions are necessary, whereas in crane motors such uniformity and small bulk are not of equal importance.

It is necessary that such motors shall, in most cases, be totally enclosed and rainproof, and that they shall be reversible; and in consequence the brushes must be fixed in the neutral position. A very high starting effort is required, leading to the adoption of the series winding, though sometimes they may be compound wound, and this possesses the useful feature we have already noted of protecting the motor from too sudden a rise in speed when the load is thrown off, but it is standard practice with traction motors to use the plain series winding.

Crane and traction motors never run at their full rated output for prolonged periods, hence the rating is the output which the motor will give for one hour with a temperature rise not exceeding 75° C., or 135° F. As a consequence of this high rating, these motors, despite the fact that they are totally enclosed, are actually smaller and lighter than the ordinary open or protected type motor for the same output on a continuous rating. Considerable modifications in the mechanical design compared with the ordinary motors are necessary, for in crane motors a brake is often combined with the motor to ensure prompt stopping as soon as the current is cut off; and, in traction motors, provision has to be made for the suspension of the motor from the car axle, and for easy inspection of the commutator and brushes from the car-shed pit.

We have already mentioned that the series-wound motor can exert a very high starting torque, with the additional advantage that the reactance voltage is low under the circumstances; for, as we have seen, the reactance voltage is proportional, other things being equal, to the speed of the armature, or, in other words, to the frequency of reversal of the coil or coils undergoing commutation. At the same time the motor is working at full field strength, as at starting the full field ampere turns are acting, and thus at the moment when the maximum current is passing through the armature the conditions are most favourable for good commutation. A crane motor by Messrs. Dick, Kerr and Co., Limited, is illustrated in Fig. 452.

This motor is of hexagonal form, and has four poles, whose cores are built up of charcoal iron stampings, the frame being of cast steel. The first view shows the motor complete with its magnetic brake, a detailed description of which is given below.

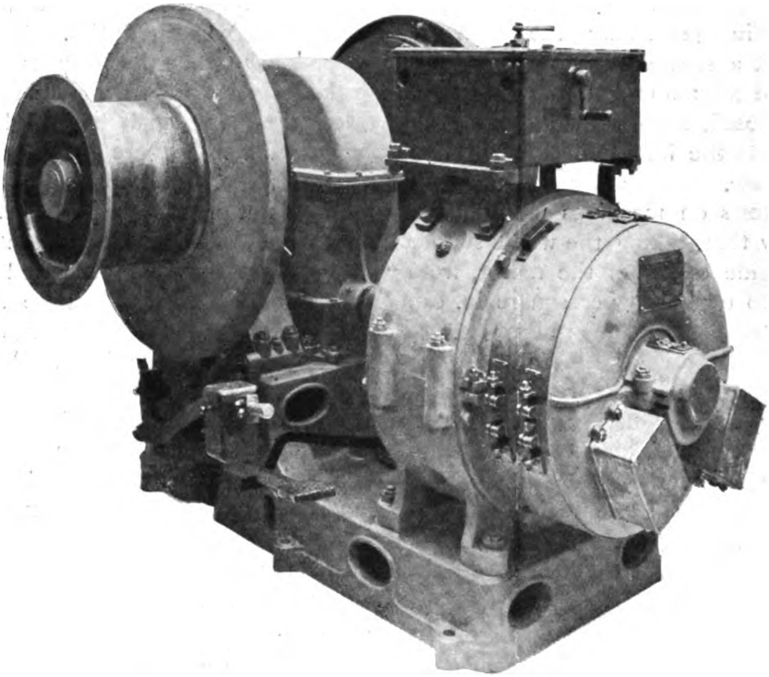


FIG. 450.—SELF-CONTAINED MOTOR-DRIVEN WINDLASS; TOTALLY ENCLOSED MOTOR, BY VICKERS, SONS AND MAXIM.

The armature core is built up of discs which are keyed direct on to a hammered steel shaft, all the windings being impregnated with high insulation black varnish, and special attention has been given to adequate ventilation; the steel carcase is provided with air ducts, the armature core has the usual ventilating ducts, and carbon brushes are employed, these being fixed at all loads.

These motors are standardised for 250 and 500 volts in sizes from 2 to 55 horse-power, the speeds varying from 450 to 800 revolutions per minute throughout the line.

The magnetic brake is illustrated in section in Fig. 453, and the description of its action, furnished by the makers, is as follows :

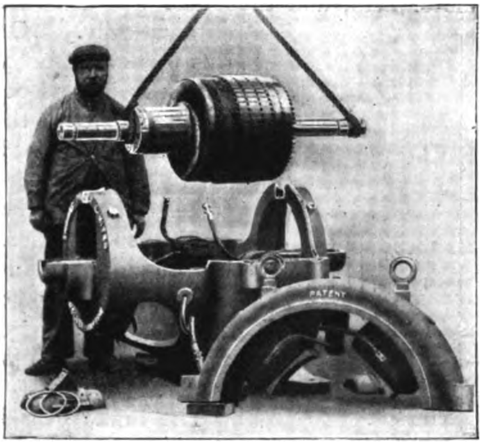


FIG. 451. — REES PATENT COMMUTATING POLE MOTOR WITH DIVIDED FIELD, BY THOMAS PARKER, LIMITED.

This brake is formed in an extension of the commutator bearing, an annular space being provided in which is carried an exciting coil, E. On the extended hub is carried a conical cast steel ring, R, which is free to move laterally ; in this ring steel springs are carried, which normally tend to push the ring away from the face of the magnet. At the extreme end of the motor shaft a malleable iron crown, C, is keyed When the motor is disconnected from the power service, the spiral springs thrust the conical steel ring into the crown. If current is switched on the electric magnet becomes energised, and the action overcoming the thrust of the springs the ring is attracted to the face of the magnet, which leaves the crown and, consequently, the shaft free to revolve.

The controller which the makers supply for this type of motor is similar in its action to the well-known standard drum traction motor controller which is described in Section X.

In Fig. 454 is shown a Laurence Scott 100 horse-power crane motor for 500 volts, running at 460 revolutions per minute, the input being 162 amperes at the normal rating.

The rating of 100 horse power is very conservative for this motor, since totally enclosed the temperature rise is guaranteed not to exceed 75° F. after one hour's run.

A reference to the performance curves in Figs. 455 and 456, will show that an output of 139 horse power can be obtained on

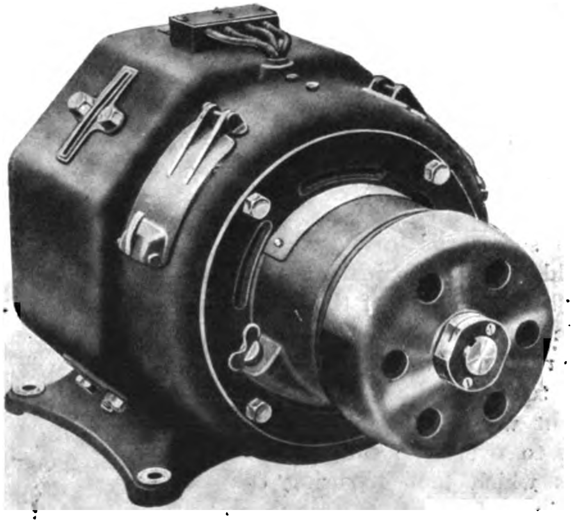


FIG. 452.—CRANE MOTOR WITH MAGNETIC BRAKE, BY DICK, KERR AND CO.

the usual basis of crane rating, namely, a 75° F. rise after the half-hour run.

An interesting feature of this motor is the combination of a hand-controlled and magnetically operated brake.

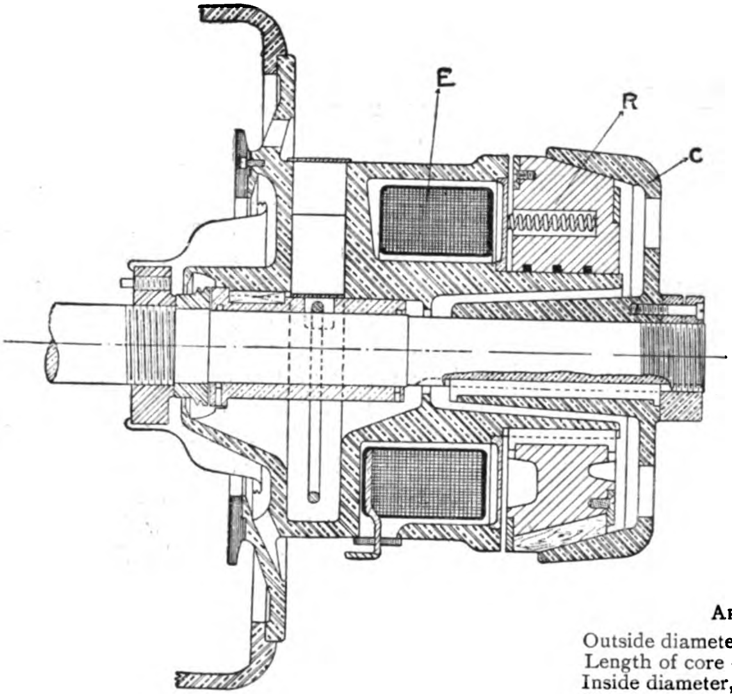


FIG. 453.—SECTION OF MAGNETIC BRAKE FOR CRANE MOTORS, BY DICK, KERR AND CO.

Two substantial cast iron "flappers" are held normally against the yoke of the motor by the leakage of the magnetic flux outside the yoke of the machine.

The resulting attraction of these "flappers" to the yoke of the machine is sufficient when the machine is normally loaded to overcome the tension of the springs which tend to bring the brake blocks in contact with the brake wheel.

This being a plain series-wound motor the possibility of the motor "running away" at light loads is guarded against by this magnetically operated brake, for if the load is eased and the motor runs up to a dangerous speed the magnetic forces acting on the flappers will also decrease, due to the weakening of the motor field, and the brake will come on automatically. On this particular motor 1,200 revolutions per minute is fixed as the maximum safe speed, and the brake comes into action at this speed, thereby corresponding to an input of about 56 amperes and about 35 horse power.

The brake gear is shown on a machine of this type in Fig. 454.

The principal dimensions of this motor are as follows:

ARMATURE.

Outside diameter	17 in.
Length of core (gross)	14 in.
Inside diameter, core	7 in.
Number of ducts ($\frac{1}{4}$ in. wide)	3
Length of core (net)	12·3 in.
Number of slots	65
Size of slots	38 in. × $1\frac{3}{32}$ in.
Conductors per slot	6
Type of winding	2 circuits
Size of conductors	0·06 in. × 4 in.

COMMUTATOR.

Number of bars	195
Diameter of commutator	11 in.
Number of spindles	4
Brushes per spindle	4
Size of brush	1 in. × 1 in.

FIELD.

Size of laminated poles	9 in. × 14 in.
Net section	120 sq. in.

The series winding consists of $35\frac{1}{2}$ turns per pole of copper strip $1\frac{1}{2}$ in. × 0·07 in. wound in two sections, the joint between the two coils being

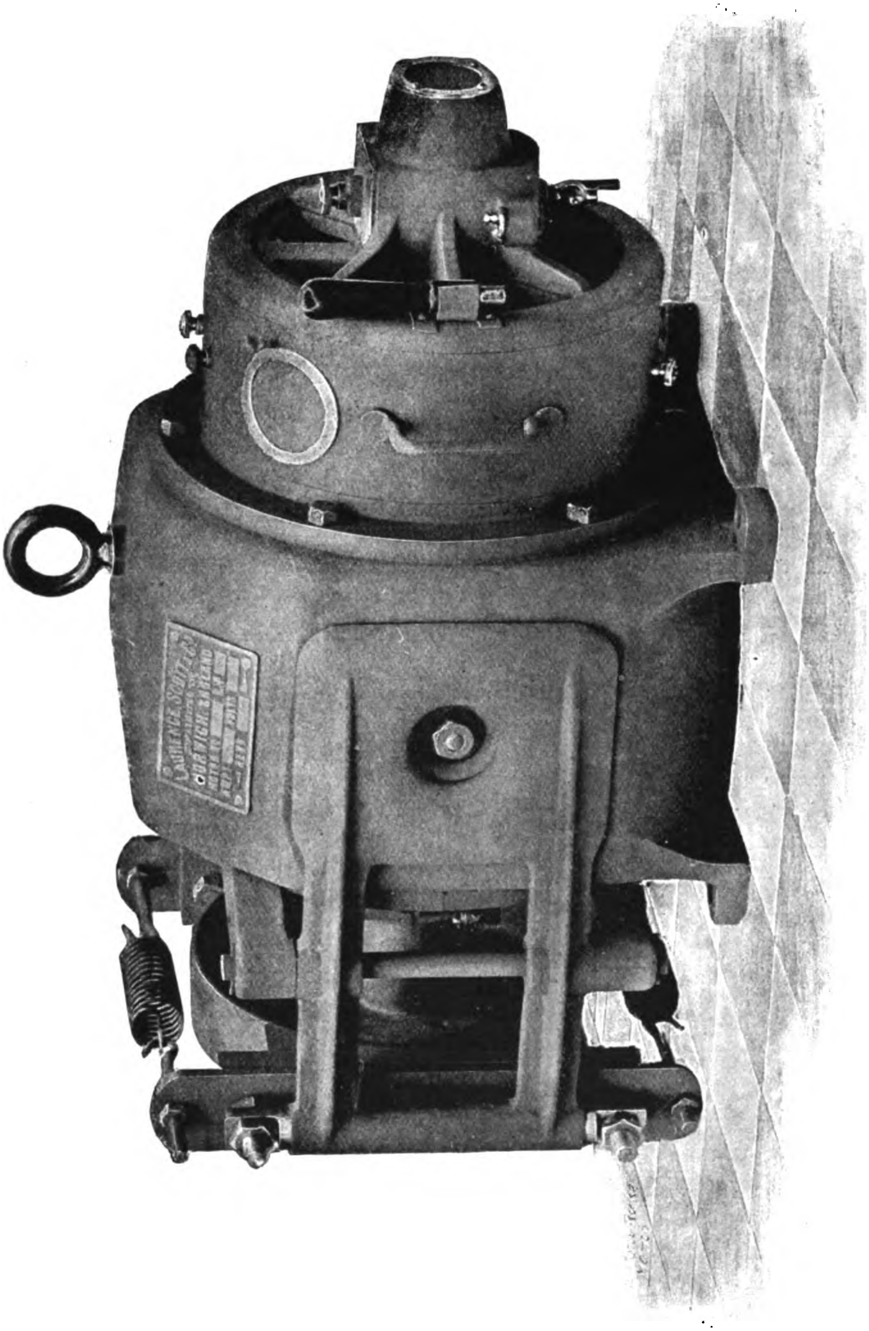


FIG. 454.—MAGNETIC BRAKE ON LIFT MOTOR BY LAURENCE SCOTT AND COMPANY.

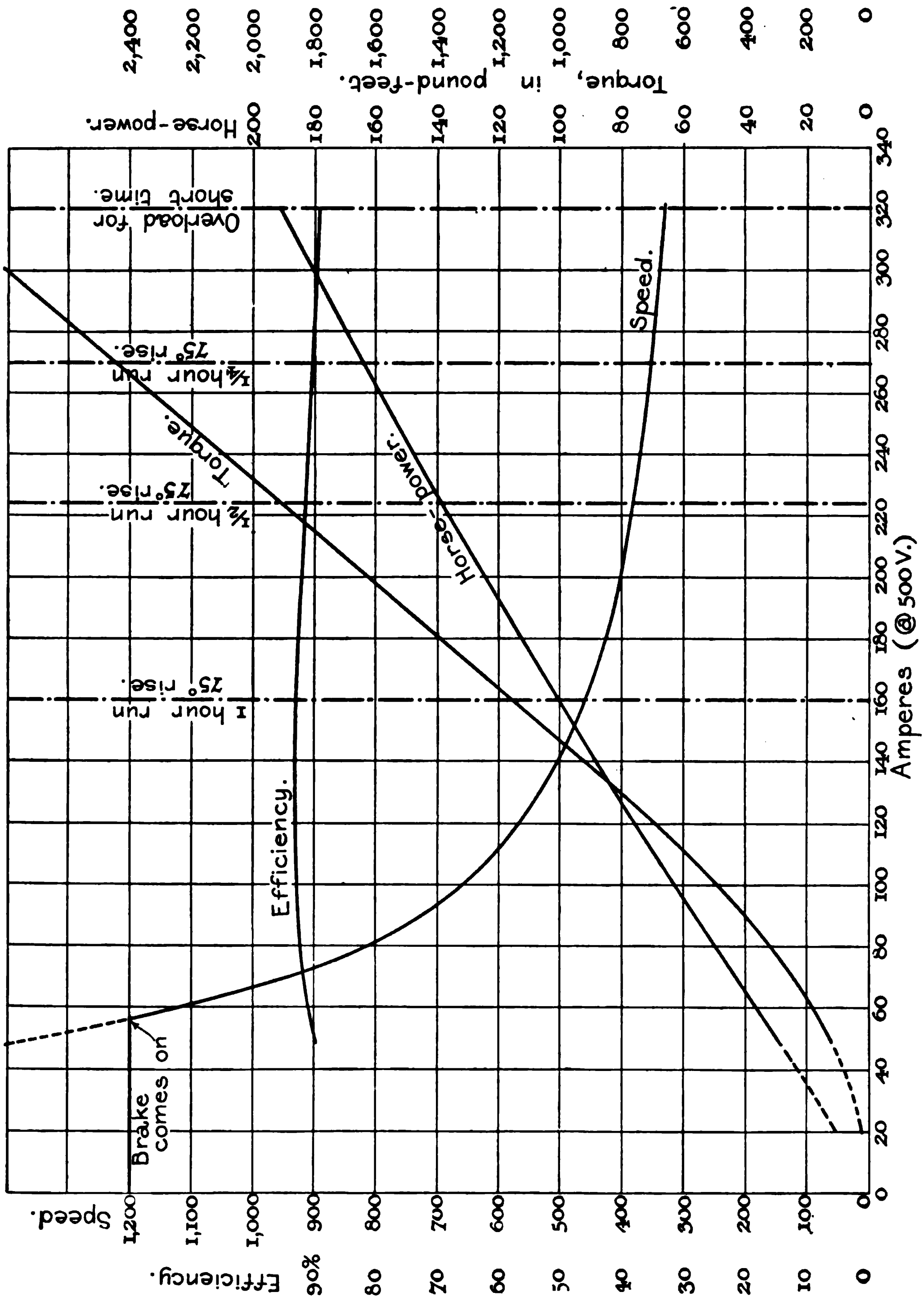


FIG. 455. PERFORMANCE CURVES OF 100 HORSE-POWER 500 VOLT CRANE MOTOR BY LAURENCE SCOTT AND CO.

made inside, thus bringing both ends of the winding outside.

The resistance of the series winding is 0·053 ohms at 100° F., while the armature resistance is 0·0865 ohms.

We can tabulate the whole losses in the motor as follows :

The performance curves are very interesting as being typical tested results on a series motor ; it will be noticed that the motor is able to stand for short periods an overload of nearly 100 per cent., while for a quarter of an hour the output is 64 per cent. greater than the nominal rating of 100 horse power.

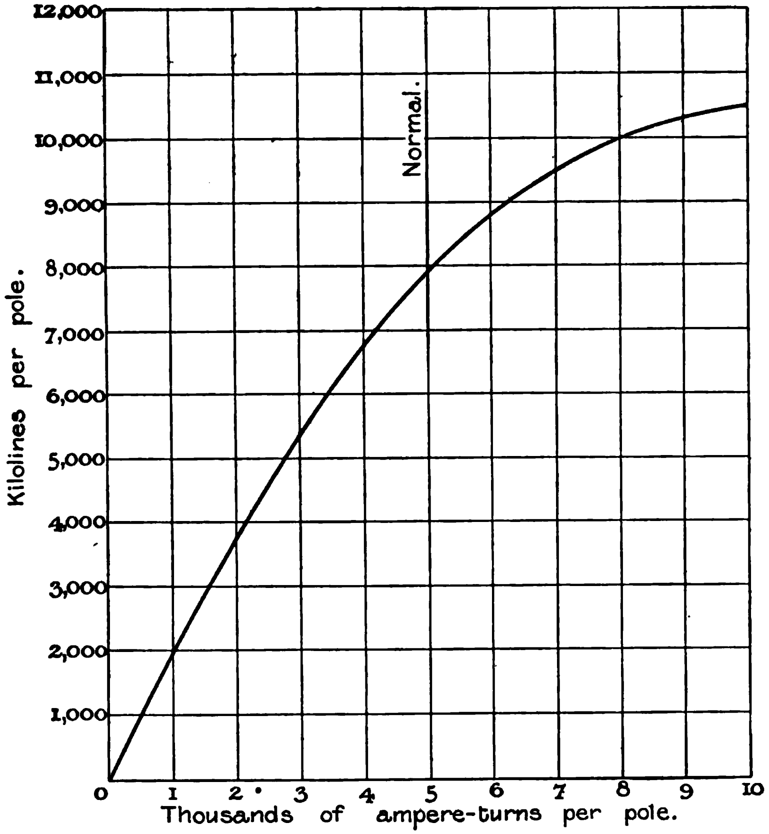


FIG. 456.—MAGNETISATION CURVE OF LAURENCE SCOTT AND CO.'S CRANE MOTOR.

Efficiency at 100 *horse power at* 460 *revolutions per minute.*

Armature C^2R watts, $(160)^2 \times 0{\cdot}0865$	=	2,200
Field C^2R watts, $(160)^2 \times 0{\cdot}053$ . .	=	1,355
Brush C^2R $160 \times 2{\cdot}5$	=	400
Core loss and friction	=	2,000
Total losses	=	5,955
Say	=	6,000
Output	=	74,000
Input	=	80,000
Efficiency	=	92·5 %

The brushes are permanently placed in the neutral position and the motor is consequently reversible.

As a typical example of a British built standard traction motor we will illustrate the Preston tramcar motor made by Messrs. Dick, Kerr & Co., Ltd.

Fig. 457 shows the motor complete with reduction gear and running axle. The motor is completely enclosed, as is neces-

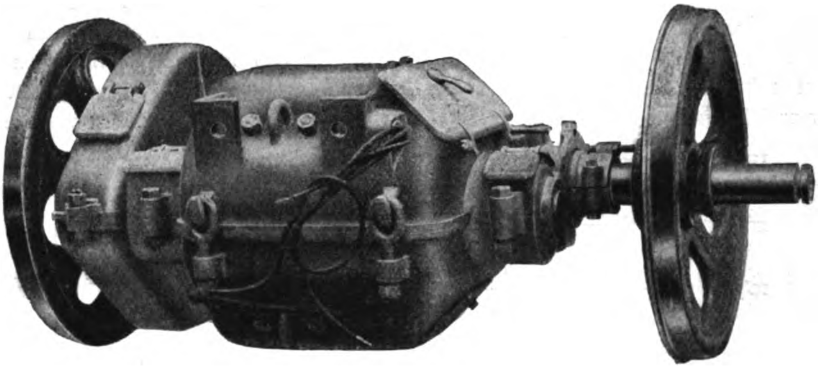


FIG. 457.—TRAMWAY MOTOR BY DICK, KERR AND CO.

sarily the standard practice for traction work, but the commutator and brushes can be inspected through the cover shown on the right, and the reduction gear through that shown on the left. Fig. 458 shows some details of the field system, and Fig. 459 shows the motor opened up for inspection, the armature and field coils being clearly shown.

The standard direct current traction motor, made in sizes up to about 150 horse-power nominal rating, and working at a pressure of from 500 to 600 volts, has not altered materially in its design during the last few years, a standard of high perfection in its electrical operation and mechanical construction having been reached as a result of the enormous number of motors which have been turned out since the birth of electric traction now nearly twenty years ago. Four-pole construction has been finally adopted throughout, as this best meets the conditions of convenient motor shape, simplicity of construction, and also gives the best commutating conditions.

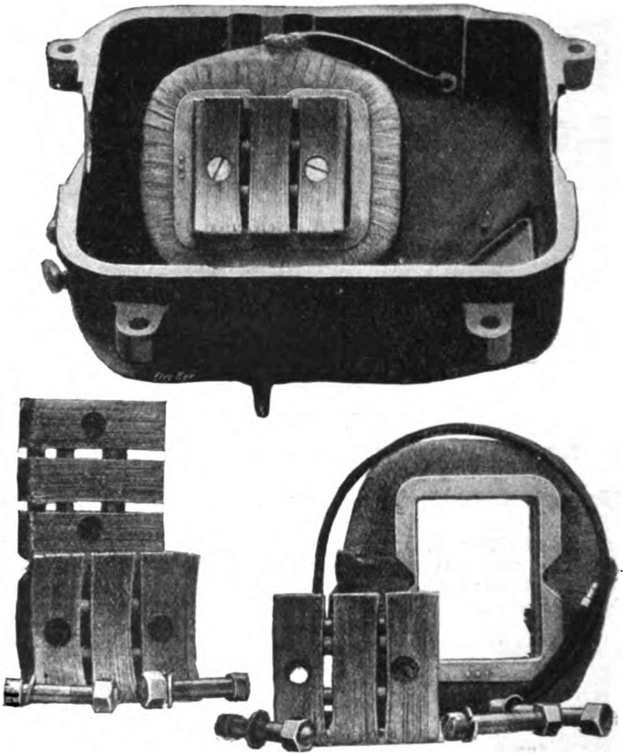


FIG. 458.—DETAILS OF FIELD SYSTEM OF TRAMWAY, MOTOR.

The increasing use which is now being

made of commutating poles on all types of direct current machinery has made it probable that these will be extensively used on traction motors with a doubling of the voltage from the present maximum of 600 volts to a trolley voltage of 1,200 or thereabouts.

Such increase in voltage will materially extend the scope of direct current traction, but it does not appear probable that direct current traction can even under these improved conditions compete in the future for heavy railway work with the new single-phase series commutator motors which seem likely to be used in such work in preference to either the high tension direct current system or the three-phase induction motor system.

But again, there seems no present prospect that the single-phase traction motor will supplant the direct current motor on tram lines, or even on inter-urban lines where the total length of the line does not exceed 10 or 15 miles, which is the economical radius of 500 to 600 volt transmission, but above this distance the single phase motor, collecting current at from 3,300 to 11,000 volts from the line possesses great advantages in spite of certain disadvantages to which further reference will be made in Chapter V.

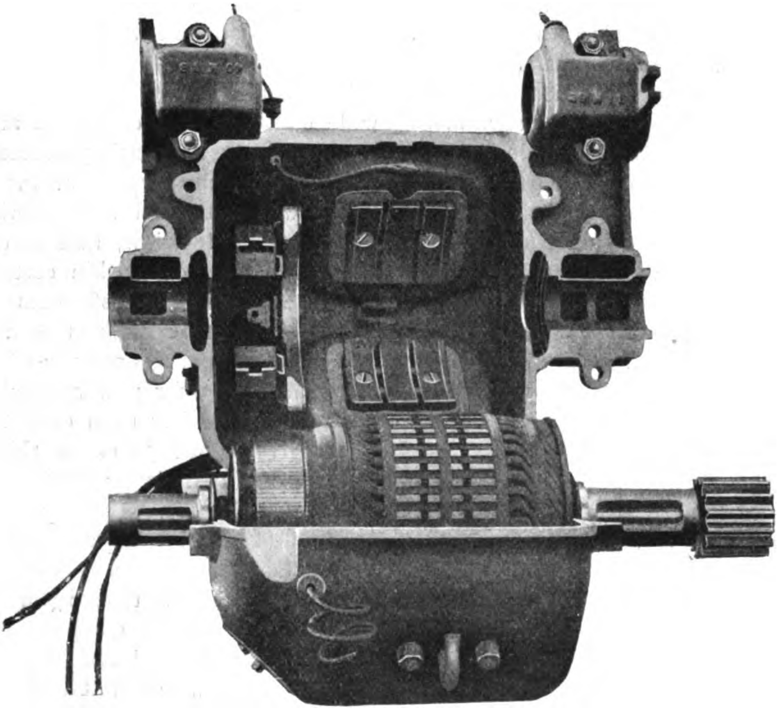


FIG. 459.—TRAMWAY MOTOR SHOWING FRAME OPEN.

CHAPTER IV.—ALTERNATING CURRENT MACHINES.

INTRODUCTORY.

In our consideration of the elementary continuous current dynamo in Chapter I., it was pointed out that such a simple machine produced fundamentally an *alternating* current, and that the addition of a *commutator* was necessary for the purpose of rendering the impulses of E.M.F. *unidirectional*, and, in an actual dynamo, a commutator of many parts must be employed to produce a true *continuous* E.M.F. It would seem more logical, therefore, to have dealt with alternating current machinery before going in detail into the design and description of the continuous current types, yet it has been usual to adopt the less logical sequence, and for very good reasons, as the action of continuous currents is much more easily followed, owing to the simpler problems involved, than is the case with alternating currents.

At first sight it would appear that there should be very little difference between a machine generating alternating currents and one generating continuous currents, because, if the commutator be removed, and a couple of slip rings substituted, we at once have a machine which will deliver an alternating current. There is an important difference, however, to start with, namely, we shall not be able to draw upon our armature to provide the necessary unidirectional currents for exciting the field, and we shall have to separately excite from an outside source. But even now the difference in principle is not great between the two machines, yet we find that, in actual alternating current dynamos or "alternators" as they are usually termed for the sake of brevity, there exists a wide departure in mechanical form as compared with the continuous current machines.

The causes which go to produce this wide constructional difference are, firstly, the fact that alternating currents must possess a definite *frequency:* incandescent lamps will not burn satisfactorily if the frequency be too low, motors demand a frequency of supply within certain limits, and the price of transformers varies to a certain extent with the frequency. The usual frequencies are 50 ∿ for general work, and 25 ∿ for power supplies, sometimes values higher than or between the limits given; but 50 ∿ in this country and the continent is by far the most usual nowadays, the 100 ∿ supply, which was in general use some years ago, having become almost obsolete.

Now, we know that in a two-pole machine we get one complete period per revolution per second, and thus, to obtain a 50 ∿ current, we shall obviously have to revolve the armature at 50 revolutions per second, or 3,000 revolutions per minute, which, except for the very smallest machines, or for dynamos driven by steam turbines, is far too high a speed. Suppose that we take a speed of 500 revolutions per minute, the top speed of the ordinary reciprocating steam engine of 100 horse-power or so, we should have to couple this to a 12-pole alternator to give a frequency of 50; or, to take the extreme case, if we wish to drive our alternator from an ordinary slow-speed horizontal engine, running at the best at about 150 revolutions per minute, we shall require no less than 40 poles for our alternator.

In practice, alternators for 50 ∿ supply, coupled to slow-speed cross-compound engines, are common at speeds of less than 100 revolutions, a 64-pole alternator at 94 revolutions being often met with for outputs of 400 kilowatts and upwards. A continuous current generator for this output at 94 revolutions per minute would probably not have more than 12 poles, and for a 500-revolution dynamo, to absorb the power of a 100 horse-power engine, probably only four, or perhaps six poles, would be employed.

The wide difference in mechanical construction rendered necessary is obvious owing to this necessity for impressing a definite frequency upon the alternating current circuit, but there is another equally important consideration which has resulted in departures in other directions from the continuous current type of generator, namely, the fact that alternating current supply has proved itself capable of much more elastic service than continuous current, alternating currents being generated to-day in some cases at 10,000 to 15,000 volts at the terminals of the machine, whereas relatively few continuous current dynamos have been built for supplying current at over 600 volts pressure.

This great difference in generated voltage has led to perhaps the greatest constructional difference, namely, the almost universal adoption of *stationary armature* and *revolving field*, the converse of the continuous current generator, for it is obviously easier to maintain good insulation on a stationary structure than a revolving one with the inevitable vibration and centrifugal stresses brought into play.

The difficulty of maintaining and providing for efficient insulation of the revolving armature of a fixed field alternator is, of course, accentuated by the fact that in general the peripheral speed of the alternator armature would be higher than in the case of the continuous current machine, owing to the inevitable increase in diameter, as compared with a continuous current machine of the same output, due to the necessity for making room for a considerable number of polar projections in the field.

The type of alternator with revolving field and stationary armature has, as we have mentioned, become almost universal, the only exceptions being very small machines or machines for low voltages, or sometimes very high-frequency generators, there still being some demand, principally in America, for revolving armature types of considerable output, the demand is, however, confined to single-phase high-frequency alternators, where the high frequency, with its attendant large number of poles, is best met by an external field design.

The requirements of practice have led to the development of alternators to supply two varieties of alternating currents: *single-phase* and *polyphase* currents; but when alternators first came into extended practical use, single-phase currents only were employed, and it was possible only to use such currents for lighting purposes, though recently single-phase motors of several different types have come to the front. But several years must elapse before this motor is received with the same favour as the continuous and polyphase alternating current motor.

The application of alternating currents to power work came later than the continuous current development in this direction, and this development has until lately chiefly been in the hands of continental engineers.

At the present time the use of the polyphase type of alternating current motor is rapidly extending, both in this country and in America; though the great developments in electric traction in the United States, and later in England, have up to the present favoured the use of continuous current machinery.

There is still a great difference of opinion as to the relative advantages of continuous and alternating currents for traction work, that is to say, the points in favour of supplying continuous or alternating currents actually to the motors on the cars, for as we shall presently see, even with a continuous current traction system, the electrical energy is often generated in the form of alternating current at high pressure, and transmitted to substations where it is transformed to continuous current at the usual pressure of 500 to 600 volts for traction purposes.

Engineers are generally agreed that for the distribution of current for lighting purposes over a large area, alternating systems have great advantages, while for small areas of distribution continuous current generators may well be installed, but all are agreed that when electrical power is to be generated and *transmitted* to any distance *exceeding a few miles* that alternating current should be generated at the power station at a high voltage and distributed to distant transformer substations where the voltage is reduced to the working pressure.

Abroad successful attempts have been made to use continuous current high-tension transmission, but at the present time this system has only been adopted in one or two instances.

The economy effected by high voltage transmission need hardly be enlarged upon here, the simple reason being that the section of copper or other metallic conductors used for carrying the current is reduced proportionately to the increase in pressure for a given energy loss in the transmission line. As to whether we shall now distribute the power in the form of alternating currents for lighting and driving motors, or transform the energy by means of motor-generators or rotatory-converters into continuous currents depends upon the circumstances, or it may be upon the prejudices of the engineer.

For lighting work there is little to choose between the two systems, but probably the advantages here are on the side of the continuous current supply, as arc lamps run more satisfactorily with continuous current, and certainly for all-round purposes the continuous current motor is to-day superior in general performance to the single-phase or polyphase motors.

It seems probable, however, that for traction work alternating currents will increase in favour during the next few years, especially because the advent of the *single-phase traction motor*, possessing, as it does, most of the good properties of the continuous current series motor, has produced a system of great simplicity, doing away with the necessity for converting the high-tension alternating currents into continuous through the medium of moving machinery at the substations.

For the distribution of current for lighting and power work on a small scale, continuous current distribution will certainly continue to be extensively used, as the storage battery is a very valuable adjunct in a small generating station, acting as a useful reserve in case of breakdown to the machinery, and also for the purpose of assisting the main generators at times of exceptional demand. It must not be forgotten also that there is a demand for continuous current by customers for the purpose of charging accumulators, and for electro-plating and other electro-chemical work.

Returning to the development of the alternating current motor and the alternator from which its currents are supplied, we may say at once that polyphase alternators came into existence principally for the purpose of driving alternating current motors, and, probably, if the development of the single-phase motor had preceded that of the polyphase motor, very little use would have been made of polyphase alternators.

Logically, it would appear that as the continuous current dynamo is a reversible machine, therefore, its near neighbour, the ordinary alternator, would also be reversible; but the analogy is incomplete, as the alternator will only run as a motor when current is supplied to it from an outside source if it be first speeded up to its normal or "synchronous" speed.

The practical application of this type of alternating current motor (the "synchronous motor") is therefore limited, as, in addition to the necessity of running it up to top speed from some outside source, the field must also be excited by continuous currents.

For one special purpose, namely, synchronous motors are extensively employed, forming a portion of the motor generator sets which are used to convert the alternating currents delivered from a distant power house to continuous currents for distribution locally. These motor generator sets consist of a synchronous motor, which is in reality nothing more than a single or polyphase alternator, coupled up to a continuous-current generator, generally delivering current at 500 volts for use on a three-wire lighting system, or for supplying power for traction. The usual objections to the use of this type of motor can in such cases be conveniently met, as the preliminary speeding up can often be accomplished by using the direct-current machine as a motor, drawing currents from the continuous-current side; but, of course, this method can be used only when there are more than one of such converter sets supplying to the continuous-current network.

Another method of starting is to make use of an "induction" or an "asynchronous" alternating-current motor to start the set from the alternating-current side: the starting motor is coupled to the main set, and is switched on when it is required to start the motor generator, and when the normal speed is reached—actually a slightly higher speed is necessary—the main motor is switched on with certain necessary precautions.

It is evident, then, that though the single or polyphase alternator is a reversible machine, and *can* be run as a motor, yet its practical utility is extremely limited. For a number of years past the only really practical type of alternating-current motor has been the induction or asynchronous polyphase motor, and to Ferraris, an Italian physicist, is chiefly due the conception of the idea which led up to the practical development of this type of motor.

Theoretical considerations induced him to believe that if he took two rectangular coils of wire, placed them at *right angles in space*, and sent two independent alternating currents through them (as shown diagrammatically in Fig. 460), these currents *differing in phase*, that he would obtain a *rotating magnetic field* within the interpolar space. He produced the necessary phase difference by dividing the current from a transformer into two branches, and introduced into one circuit a choking coil, the inductive effect of which was sufficient to produce a considerable displacement in phase between the two circuits.

He found that, if a copper cylinder were introduced into the interpolar space, the cylinder rotated when the two coils were excited ; next he introduced an iron cylinder with the same effect, and he also found that the direction of rotation could be reversed if the current were reversed through one of the coils.

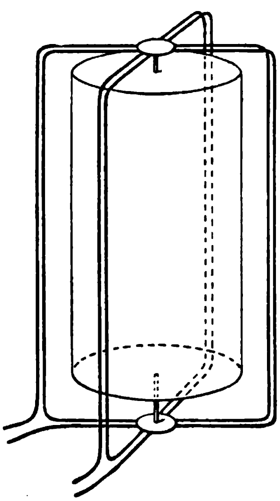
The cause of the rotation can be explained simply, as follows : The revolving magnetism induces eddy currents in the face of the metallic cylinder, and the interaction between these induced currents and the revolving field tends to produce motion. As a familiar instance of the induction of currents in a rotating metallic disc, and an instance of how a braking action is caused when the disc is revolved mechanically and in a magnetic field, we may cite those types of electric meter, such as Elihu Thomson's, in which a thin disc of copper is revolved by the meter mechanism between the poles of permanent magnets, eddy currents being set up in the disc, and producing a retarding action on the meter. From analogy we should expect that, if we rotated the magnets, that the disc would revolve, and the experiment to demonstrate this fact, known as Arago's Rotations, is frequently performed in the lecture room.

This apparatus is shown in Fig. 460.

Referring to Fig. 460, when the cylinder is prevented from turning by being forcibly held, the coils being excited, eddy currents of considerable magnitude are induced in the metallic mass, and a large starting torque is exerted, and if now the cylinder is allowed to run up to speed, there will come a point when the magnitude of the induced currents will diminish, and when the cylinder is running free, having to exert only sufficient torque to counteract the friction of the bearings, the currents flowing will be very small, and the speed of the disc will depend entirely upon the *number of poles* produced by the primary winding and the *frequency* of the alternating currents supplied, exactly as the frequency of the current supplied by an alternator is a function of the speed and number of poles.

Practically, the actual speed will be slightly less than the "synchronous" speed, as at the synchronous speed no torque whatever would be exerted, but this is an impossible state, as frictionless bearings are, of course, impossible.

When the motor is called upon to take up load the speed falls more and more away from the synchronous speed, until, finally, if the load is increased too much, the motor stops ; it would, however, run up to speed again if the load were eased.



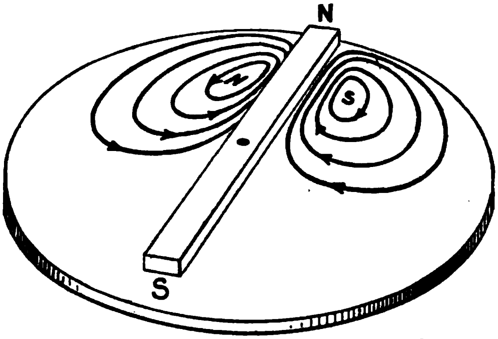


FIG. 460.—EDDY CURRENTS IN DISC UNDER REVOLVING MAGNET.

Technically the motor is said to "slip" as the load comes on, and the slip of a motor is the amount of slowing down relatively to the synchronous speed.

The induction motor does not permit of any great speed variation, as after the motor has been loaded up to a certain critical point the torque diminishes suddenly and the motor slows down ; and, in fact, considerable speed variation can only be obtained by designing the motor to give a large " slip," and this can only be done to a certain extent, and at the sacrifice of a great deal in the general performance and efficiency of the motor.

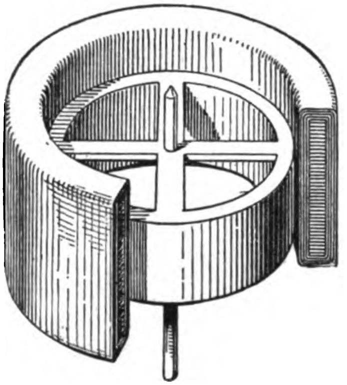


FIG. 461.—ELEMENTARY INDUCTION MOTOR WITH SOLID ROTOR.

The speed can, of course, be varied by changing the frequency of the supply, or the number of poles produced by the winding, but it is quite out of the question to change the frequency of a supply for the benefit of an individual motor, and the switch-gear necessary for the purpose of changing the *number of poles* by altering the connections of the winding is very clumsy, and this method is rarely resorted to, though it has been occasionally employed.

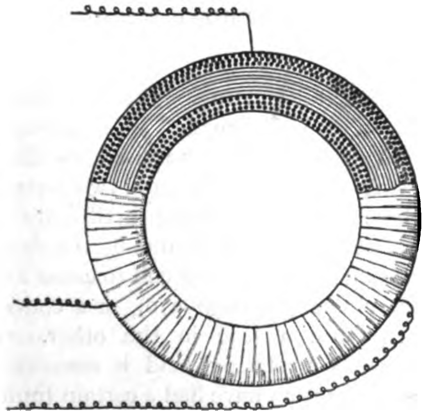


FIG. 462.—THREE-PHASE TAPPINGS TO A RING WOUND WITH A CONTINUOUS COIL.

In all practical motors the primary windings are embedded in an iron core; Fig. 461 shows a primary winding wound over an annular laminated iron core with rotating cylinder, and Fig. 462 shows how tappings for three-phase currents would be taken to such a wound ring; in all modern motors, however, as we shall see in Chapter VI., the arrangement of the windings is different, though the essential principle is the same. The plain copper cylinder also is modified, Fig. 463 showing an early prototype of the modern revolving portion of the motor, called the " rotor," the fixed iron core receiving the primary windings, being called the " stator." The rotor here shown consists of a skeleton copper cylinder lined on its inner periphery with a laminated iron core.

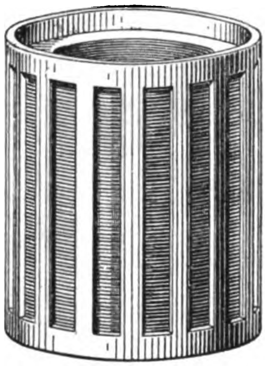


FIG. 463.—EARLY ROTOR HAVING PERFORATED COPPER SLEEVE OVER LAMINATED IRON CORE.

The stator takes the form of a continuous ring of rectangular section built up of sheet iron stampings, as shown in Fig. 534, Chapter VI., and the inner periphery of these stampings is slotted to receive the windings, which are so arranged that when the alternating currents, differing in phase, circulate through the winding, a definite number of polar regions are produced. When the current is switched on to the windings we may consider the magnetism of these polar regions to revolve at the synchronous speed of the motor.

The rotor is similarly built up of sheet iron stampings, with holes or slots on the outside periphery, as is well shown in Fig. 535, Chapter VI., these slots receiving copper windings, which may either consist of coils of insulated wire threaded through the slots, or the "winding" may take the form of heavy bars, connected at each end to a substantial metal ring, the whole forming an electrically connected skeleton cylinder embedded in the iron, clearly shown in Fig. 536, Chapter VI. This would be called a "squirrel cage," or short-circuited rotor.

The stator windings may be either of the two-phase or three-phase variety, or such a motor may be wound with a winding for single-phase, and will run as a single-phase "induction" motor if some special arrangement is made for starting it up; with a simple single-phase winding, this type of motor possesses, in common with the synchronous motor, the disadvantage of not being self-starting. Such a motor, however, can be made self-starting if an auxiliary winding be used to divert the single-phase supply into two circuits, a phase difference being artificially set up between the two circuits by the device of introducing a choking coil to cause a lag in one circuit (*see* page 370), or a condenser to cause a lead in the other. By this means a rotating field is *simulated*,* and such motors have had a certain limited

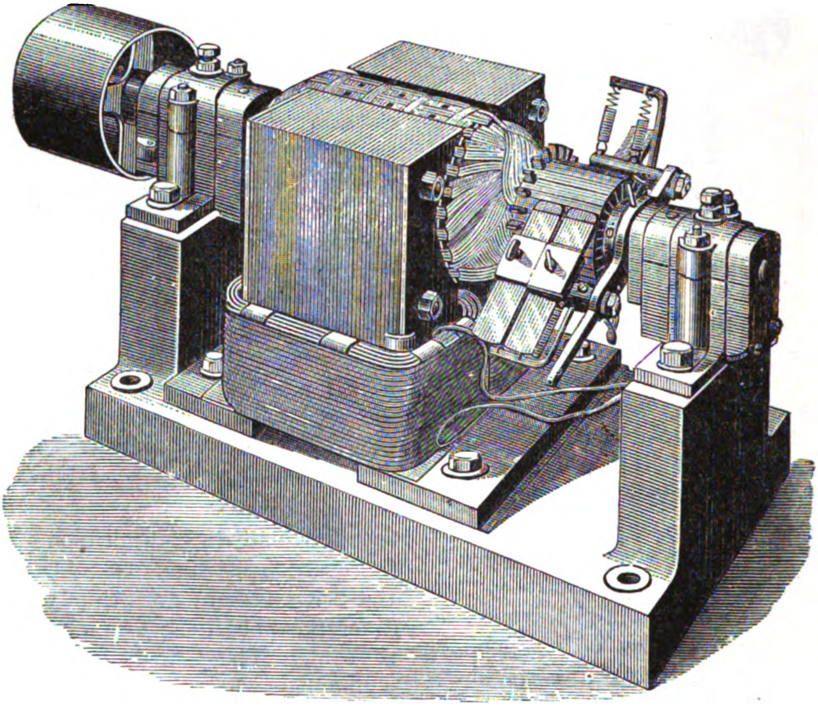


FIG. 464.—EXAMPLE OF EARLY SINGLE-PHASE SERIES COMMUTATOR MOTOR WITH LAMINATED FIELD.

---

* The field may fairly be said to rotate, but the rotation and field strength are both irregular.

application on single-phase supplies. One of the best of these motors is the Heyland single-phase motor, in which a fair performance as regards starting is obtained in a slightly different manner to that which we have described, the principle of its action, however, being the same.

To return to the ordinary polyphase induction motor, it is fairly obvious that it has its limitations compared with the continuous-current motor.

The induction motor can be designed to give a fairly large starting torque, hardly equalling that, however, of the continuous-current motor, and the speed is, apart from rather complex and unsatisfactory devices, nearly constant at all loads; for traction these features detract very greatly from the utility of the induction motors. The induction motor also has other disadvantages, which we shall deal with later when the performance of these motors is more fully discussed.

There is no doubt that for some purposes the induction motor scores heavily on account of the absence of the commutator, which is the one great disadvantage of the continuous-current motor.

With all its disadvantages, however, the induction motor has been used extensively on the Continent for traction work, the speed regulation being effected to a certain extent by what is known as the "cascade" method of regulation, analagous in some ways to the series-parallel control used in continuous-current traction.

The new types of single-phase motor which are now coming into use will probably, as we have already mentioned, effect almost a revolution in heavy traction, and we will merely mention the type which has been most extensively used, namely, the *series alternating motor*, which is in principle nothing more than an ordinary series continuous-current motor with a *laminated field system*. Fig. 464 shows a very early motor of this type built in France as early as 1888, but it ran very imperfectly with alternating current, the brushes sparking badly; but much ingenuity has, since that time, been displayed in so modifying this type of motor as to make it a practical success. This type of motor, and others which have recently been made a practical success, will be more fully mentioned in Chapter VI.

CHAPTER V.—ALTERNATORS AND TRANSFORMERS.

ALTERNATORS: TYPES—FIELD—ARMATURE—E.M.F.—IRON LOSSES—POWER FACTOR—PRESSURE REGULATION—PARALLEL RUNNING—TURBO ALTERNATORS—EXAMPLES OF TURBO ALTERNATORS.

TRANSFORMERS: SPECIFIC CONSTRUCTIONS—WELDING TRANSFORMERS.

Before making more detailed reference to the design and construction of modern alternators, brief mention must be made of a type which, though fast going out of favour, still finds a limited vogue. The advantage inherent to the revolving field type, by reason of the armature windings being stationary, has already been pointed out. It is possible, however, to pursue this feature still further by arranging matters so that there shall be no moving copper at all, that is to say, the exciting coil or coils shall be stationary, as well as the armature windings, making slip rings quite unnecessary, so that there is only iron in the rotor. The moving iron is called the "inductor," and the type of machine is known as the inductor type. The principle of the type was enunciated in a patent taken out by Prof. S. P. Thompson in 1883, and machines embodying the principle were built by Mr. Kingston some years later. In these machines the stator consisted of a ring built up of laminations with internally projecting radial cores like pole cores. Alternate cores were wound with magnetising coils, while the remainder carried the windings which should generate current, *i.e.* armature coils. Tracing the cores round in succession there would be N pole, armature core, S pole, armature core, N pole, and so on. The rotor, or inductor, consisted of laminated polar masses projecting radially outwards, and carried on a hub or wheel. The angular width of an inductor pole was exactly equal to the sum of that of a magnet pole and armature core, plus the gap between them. Reference to Fig. 465 will show that the rotation of the rotor caused alternations of flux through the armature cores, because an inductor pole would complete the magnetic circuit through a core with a N and S pole alternately on either side of the armature core, and thus an alternating E.M.F. was generated in the windings. If all the armature coils or some of them, are connected in series, those so connected must be wound alternately clockwise and

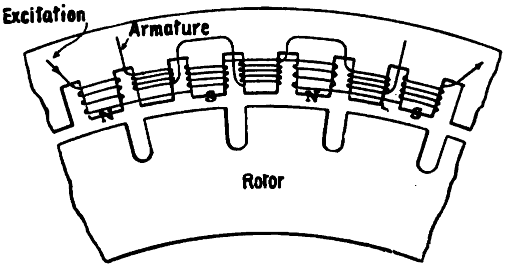


FIG. 465.—PRINCIPLE OF INDUCTOR ALTERNATOR.

counter-clockwise so that the E.M.F.s may all add up.

It will be seen from a consideration of Fig. 465 that there was a considerable mass of iron associated with an alternating flux and hence a correspondingly important hysteresis loss. Later designs have reduced this, and have confined the fluctuation of field to a comparatively shallow depth of iron. Moreover the many magnet coils of the Kingston type have given place to a single coil and, instead of an alternating flux a *fluctuating* one, of invariable sign, is employed to generate the E.M.F. This will be understood by reference to Fig. 466. The field winding consisted of one large coil (though in two halves axially) of about the same diameter as the inner diameter of the stator, and supported from the stator by a ring of inverted **T** section, the two halves of the coil being wound one on each side of the web of the **T**. The magnetic field from this coil would be as indicated by the dotted line, and would therefore thread *two* armature coils and *two* air-gaps. The armature coils are arranged in two rings, one on each side of the stator, those on one side being seen on the right hand of the illustration. The rotor carries half as many inductor poles as there are armature coils, and these poles are arranged axially in pairs: each inductor pole carries a laminated tip and the armature coils are wound on laminated cores. Fig. 467 shows the inductor of a 750-kilowatt machine by the Oerlikon Company.

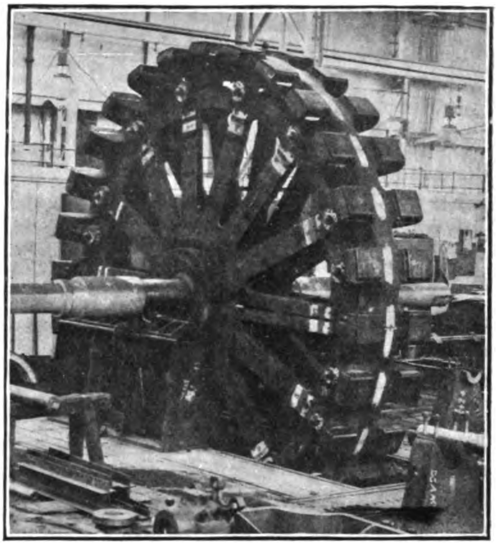


FIG. 467.—INDUCTOR OF LARGE INDUCTOR TYPE OF MACHINE.

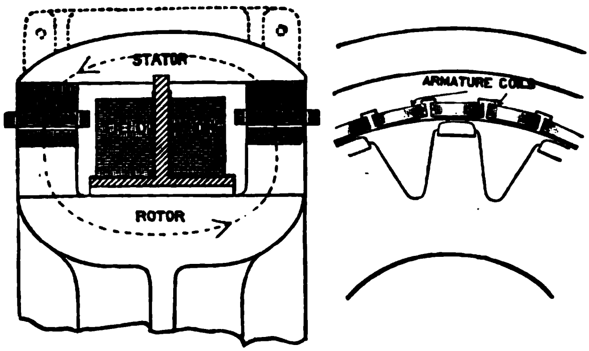


FIG. 466.—MAGNETIC CIRCUIT OF INDUCTOR ALTERNATOR.

We shall refer presently to the great importance of the voltage regulation in alternators, but we may mention here that inductor alternators give satisfactory results if they are only used for lighting or other "non-inductive" loads; but for power work, *i.e.* for supplying power to motors, they are unsatisfactory, and there are several cases on record where large and expensive alternators of the inductor type have proved utterly worthless when used for such work, and have had to be replaced at great cost by machines of the wound-pole type.

The revolving field alternator, with every pole wound, must therefore be considered as pre-eminently the modern type, and practically all the machines which we shall illustrate in this chapter will be of this description.

FIELD EXCITATION.

We cannot, of course, draw current direct from the armature for exciting the field, but we may commute part of the armature current for this purpose, though it is not feasible in the majority of cases. Current is sometimes drawn from the armature and rectified by means of a commutator, and these rectified currents are then sent through the field winding. Excitation is almost invariably provided for by a suitably proportioned direct current machine built for the purpose and termed the exciter. The exciter may be mounted on the shaft of the alternator, or may be driven by belting or ropes from a pulley on the alternator shaft; or, of course, the necessary exciting current can be drawn from any other continuous-current supply. The exciting current is supplied at a low pressure, and conveyed through slip rings into the revolving field quite easily without any of the difficulty which would ensue if we had to collect the main current of the alternator, probably at high voltage, from the slip rings, as would be the case with a revolving armature; and we see, therefore, that there are very great advantages on this score alone in favour of the revolving field alternator.

ARMATURE WINDING.

As we have already dealt in detail with the design of continuous-current machines, and as it has been already pointed out that, in principle, the induction of currents in the alternator armature differs in no wise from that in the continuous-current machine, it would appear at first sight that very little further discussion would be necessary. There are, however, factors controlling the design, and especially the working of alternators, which necessitate close consideration of the process of induction in an alternator armature, especially as we have to consider the question of polyphase windings. We will therefore start with the consideration of the induction of currents in the armature of a simple revolving field type alternator. We can consider two adjacent poles, N and S, forming part of the alternator flywheel, the stationary armature being outside. For simplicity, consider a loop passed through two slots one under each pole. It is then obvious that the poles, as they revolve, sweeping their flux through the armature, will induce, at any given instant when the loop is under the influence of the poles, currents in opposite directions in the two sides of the loop, and as the two ends of the loop are connected, the total voltage induced in the loop will be twice that induced in one side. Now we could obviously wind more than one turn through the two slots, and the voltage induced would increase in proportion to the number of such turns. If we had, instead of continuing the winding through the same pair of slots, moved on to a third slot under a third pole, then on to a fourth slot under a fourth pole, taking care, in passing from one slot to the next, to keep on the same side of the armature, and to cross the armature only through a slot, we should find the voltage add up in proportion to the number of conductors in the slots, thus forming a wave winding. Returning now to the simple coil winding with many turns in each coil, this winding instead of being concentrated in a single slot under each pole, may be wound in a number of slots under the two poles. In Fig. 468 two windings are shown, both with four slots under each pole. All the conductors in the slots, as the poles revolve, will have the same voltage induced in them, and the total voltage induced at the ends of the winding will be the same in the two cases shown. It does not follow, however, that the voltage is independent of the spacing, or that the arrangement of the conductors is unimportant ; it is, in point of fact of extreme importance, as a very simple consideration will show how a bad result may be arrived at if this point is neglected.

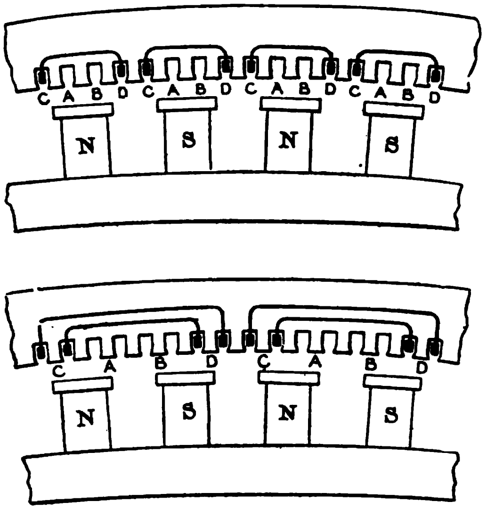


FIG. 468.—SINGLE COIL (ABOVE) AND DOUBLE COIL (BELOW) WINDINGS FOR SINGLE-PHASE WORK.

If we consider one turn wound through the adjacent slots, A and B, we see that, at the instant when it is directly under a pole face, voltages will be induced in the same direction in both sides of the loop, and that though each conductor is generating at this moment its maximum voltage, yet the voltages in the case of these two adjacent conductors will exactly neutralise one another, and the result will be that there will be no difference of voltage between the two ends of the loop.

It is of prime importance for anyone approaching the subject for the first time to realise that there is a time element to be considered, and that the total E.M.F. of the winding of q conductors is not necessarily q times the E.M.F. in each conductor. If the conductors are so placed that all are *similarly* affected at the same moment, *i.e.* all arrive at their maximum at the same instant and so on, in a word, if there be no phase difference between them, then the total E.M.F. will be the arithmetical sum, viz. q times the E.M.F. in each conductor. When, however, spacing of the conductors is such that all do not arrive at their maximum E.M.F. simultaneously, but there is a phase displacement between neighbours, the total E.M.F., all being in series as before, is only arrived at by taking the vector sum at every instant, and in such cases this will be found to be less than the arithmetical sum. The ratio of the maximum in the one case to that of the other is determined by degree of total phase difference between any wires connected in series. The actual spacings in an armature, such as will produce the two kinds of effect, are indicated in Fig. 469. The upper winding shown in the figure has the conductors grouped together in single slots, the others being left vacant, and is called a concentrated winding, while the lower one has the same number of conductors distributed among as many slots as there are conductors, and is called a distributed winding. It need hardly be said that, although the diagram shows a bar winding, each conductor being constituted by a stiff bar, for higher voltages each coil of a single turn may be replaced by one of many turns, in which case even in the distributed winding each slot will carry many wires. The distributed winding shown in Fig. 469 is an extreme case, taken for the sake of emphasis, for a modern single-phase winding never occupies the whole armature surface as is there suggested. There are various reasons affecting cost and rapidity of manufacture, which make it desirable for the manufacturer to keep the variety of armature stampings which he uses down to a minimum, and it is no unusual thing to find a completed armature having many unwound slots, the empty slots serving no useful purpose in the machine, but being there to enable the same stampings to be used for other designs. Some variation is thus usually possible in the degree of distribution of a winding, and a winding is commonly found where a coil edge occupies two or three slots, as in Fig. 470.

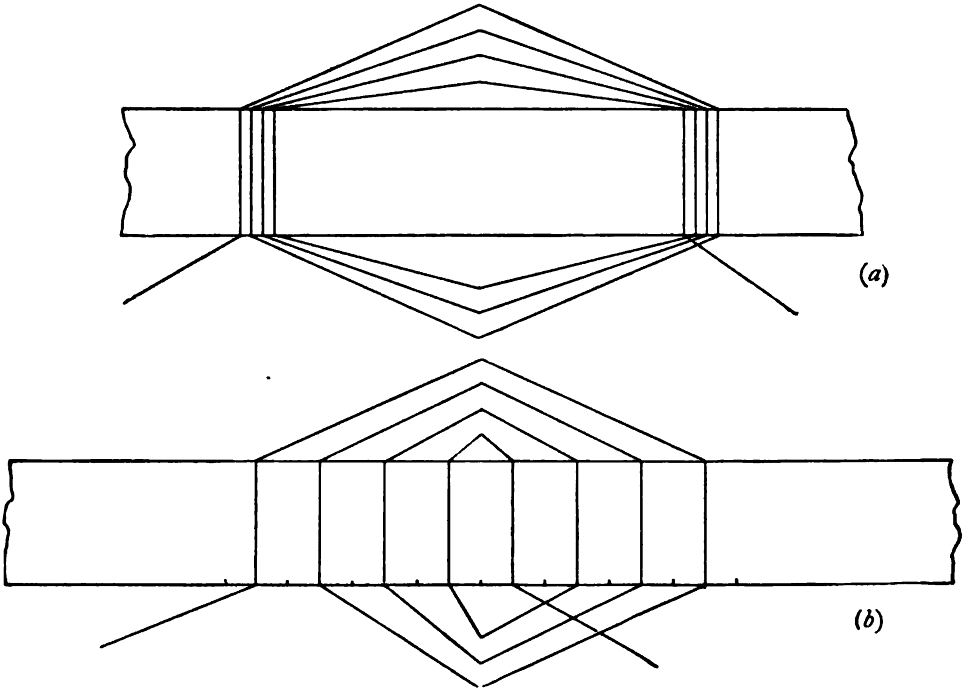


FIG. 469.—DIAGRAM OF DEVELOPED ARMATURE SURFACE, SHOWING DISTINCTION BETWEEN CONCENTRATED WINDING (ABOVE) AND DISTRIBUTED WINDING (BELOW).

If the pole width and flux distribution are such that any single conductor or group of conductors in one slot is the seat of a truly sine wave of E.M.F., the effect of a distributed winding is to produce a sine wave, but of less amplitude, as is shown in Fig. 471. There is an effect, however, due to the ratio of pole width to pole pitch which modifies the resulting E.M.F. It is not possible within the scope of an elementary work like the present one to enter into a discussion of these effects or of the production of harmonics, and the reader is referred to such treatises as Prof. S. P. Thompson's "Dynamo Electric Machinery," Vol. II. or Prof. Gisbert Kapp's "Dynamos, Alternators and Transformers," and other works for a full treatment of the subject. The coefficient by which the voltage for a perfectly concentrated winding, as in (*a*), Fig. 469, must be multiplied to give the voltage of the distributed winding of equal turns (*b*), Fig. 469, is called the "breadth coefficient," or Kapp coefficient.

Later on, we shall give data to enable the necessary correction to be made for these effects. It will be seen, then, that in a winding of this kind, that is, in a *single-phase* winding, only about *half* the periphery of the armature can be effectively utilised, since it would be useless to fill up the vacant slots by distributing the winding, as the inner turns would neutralise each other in an increasing degree the more closely they approach each other. As a single-phase winding, with four slots per pole given, nothing better can be done; but what we could do would be to wind the armature in two separate and completely independent circuits, each winding occupying half the slots. Instead of winding through the *adjacent* slots, A and B and A and B, we might wind right across the first winding by bending up the ends of the coils so that both windings were symmetrically situated and spanned over approximately a pole pitch. Obviously, electrically, both windings would be the same, would both induce the same effective voltage. We could thus take a single-phase machine, and, by putting in the extra winding, *increase* the output. We should not *double* the output, for reasons that we shall see later, but still we should get more out of the machine. Though the voltage induced in the two circuits would be the same, yet these windings could not be connected in parallel, as the *voltages* would not be in *phase.* In fact, we should have two alternating currents *in quadrature*, or what are known as *two phase* currents. A complete cycle, or, in other words, a + and — wave, can be considered as representing an angular displacement of 360 degrees, this corresponding to two pole pitches; and as the coils on the armature undergoing induction are displaced by half a pole pitch, the phase of the induced voltages will differ by 90 degrees. Fig. 472 shows the single-coil and double-coil windings for the two-phase case analogous to the single-phase case of Fig. 468. By a simple modification we could use three such windings on the armature to generate three-phase currents. When we come to the three-phase case, it is necessary to adopt a kind of winding which differs practically, though not electrically, from the single- and two-phase windings which we have described. The three-phase case is shown in Fig. 473 with the alteration that there are six slots per pole instead of four, since a three-phase winding cannot properly be arranged in the four-slot stampings. On looking at the way in which the end connections have to cross each other in the single-coil winding the need for bending them clear of one another

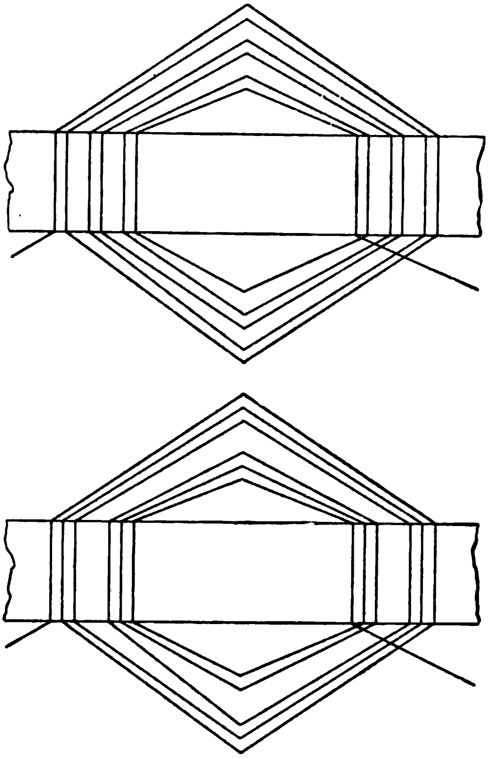


FIG. 470.—UPPER WINDING HAS THREE AND LOWER HAS TWO SLOTS TO EACH COIL "EDGE"; NUMBER OF TURNS IS THE SAME IN BOTH.

in three "ranges" is abundantly obvious. The difficulty is avoided in the double-coil winding, and this is therefore almost always used for both generators and motors. The windings of three phases are marked 1, 2, 3, in the diagram, and it will be noted that they are relatively displaced by two-thirds of a pole pitch, or 120 degrees of a cycle of 360 degrees. The double-coil winding has also been called "hemitropic," to distinguish it from the "single-coil" windings. To avoid confusion, however, we shall use the terms single- and double-coil windings, as no distinguishing name has in general been applied to the single-coil windings. Single-coil windings are generally adopted for single- and two-phase machines from practical considerations, the double-coil or hemitropic windings only being used when the top half of the armature of the machine must be capable of being lifted off without disturbing the winding. Three-phase machines are practically always wound with the double-coil windings, not because it is impossible to use the single-coil winding on three-phase armatures, but because such a winding introduces practical difficulties.

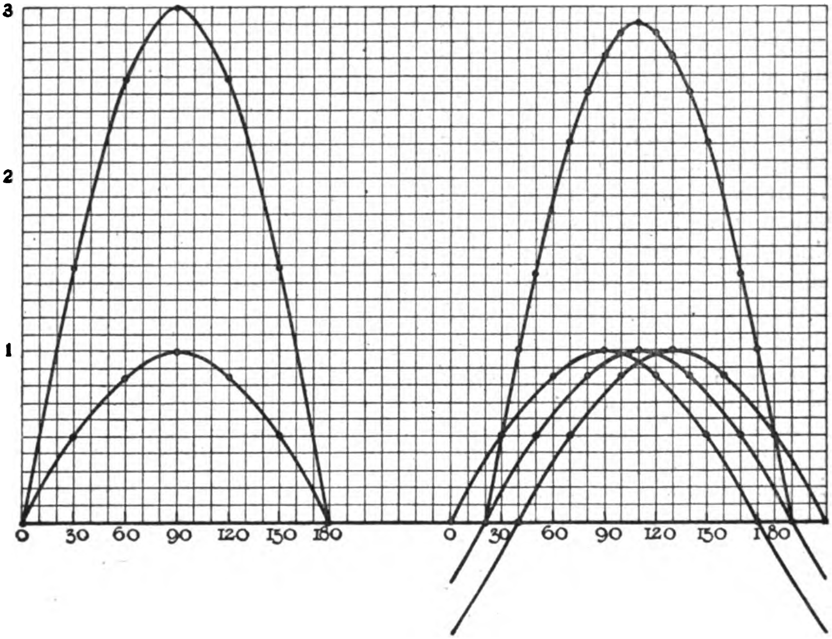


FIG. 471.—SUMMATION OF E.M.F.S IN THREE BARS, ON THE LEFT, ALL THREE IN ONE SLOT; ON THE RIGHT, DISTRIBUTED SO THAT EACH IS 20 DEGREES OUT OF PHASE WITH ITS NEIGHBOUR.

The practical difficulty inherent in the single-coil three-phase winding is that if one phase is wound with the ends of the coils standing straight out, and a second has the ends bent up to escape the first, the third must have its ends bent down (the windings are then after described as the "straight," "bent-up" and "bent-down" phases); and the bent-down

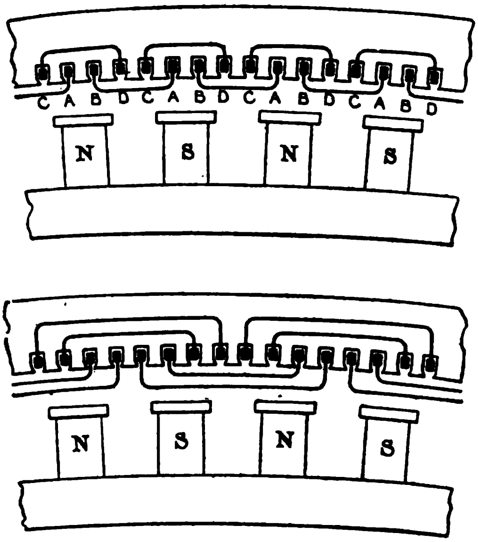


FIG. 472.—SINGLE-COIL AND DOUBLE-COIL WINDING FOR TWO-PHASE WORK.

ends prevent the armature from being slid along the base parallel to the shaft for the purpose of repairs, dismantling, etc., since they would foul the magnet wheel. Even when the top half of the armature has been lifted the lower half still fouls, and the magnet wheel must be lifted out of its bearings before any great axial displacement can be effected.

ARMATURE SLOTS.

The factors which influence the number and size and shape of the armature slots of an alternator are many, the chief being the type of winding; that is, whether there is only one conductor per slot (as is often the case in low-voltage machines), or whether many conductors of small cross section must be placed in each slot (as occurs in high-voltage machines or machines of small output).

Alternator windings may be divided into two broad classes, viz. those with hand-wound coils and those with former-wound coils, and the price of labour will largely influence the adoption of the one type or the other.

If winding labour is cheap there will be a tendency to adopt hand windings, and in this case the advantages of an almost completely closed slot will be seized; but if labour is dear, every effort will be made to use former-wound coils as frequently as possible, an open slot being used despite its disadvantages, to allow of the coils being wound up and insulated, before being slipped into place and secured there by wedges of wood.

As regards the electrical design of the machine, all the advantages are in favour of an almost closed slot (a completely closed slot is not advisable, as the pressure regulation of the machine is thereby impaired), and the slot with an opening towards the poles equal to about one half the radial depth of the air gap possesses the advantages that the excitation is decreased for a given length of air gap,

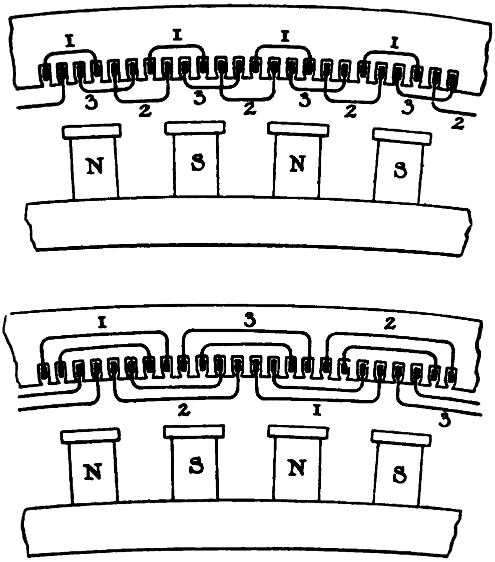


FIG. 473.—SINGLE-COIL AND DOUBLE-COIL WINDING FOR THREE-PHASE WORK.

the coils are better protected mechanically, it is easier to obtain the desideratum of an approximately true sine wave form, and eddy currents in the pole faces are reduced very considerably as compared with the quite open slot.

When a bar winding can be used, or when the winding does not consist of more than five or six conductors per slot, the advantages are certainly on the side of the hand-wound coils, but in the case of high-voltage machines, those of small output necessitate the employment of a large number of small conductors per slot, the cost of labour in winding will more than off-set the electrical advantages, and former-wound coils and open slots will be chosen.

The greatly superior facility in making repairs with former-wound coils need hardly be pointed out, and for machines operating in out-of-the-way districts there is a very strong case for former-wound coils, merely on the score of easy repairs.

As regards the number of slots, modern practice does not vary very much. For each phase of the winding there must of course be at least two slots per pole for the single-coil windings, or two slots per pair of poles for the double-coil windings. In practice, however, such concentrated windings are not used. The maximum number of slots usually desirable is four slots per pole per phase, but three slots per pole per phase is a very common number, though four or five may be employed for very large, low-frequency alternators.

Adequate slot insulation, that is slot lining, must be employed according to the voltage used, and since for high-voltage machines the amount of slot insulation employed must steadily increase with the voltage, while at the same time the number of conductors which must be crowded into a slot will also increase, it is evident that the "space factor" of the armature slots will diminish very rapidly with increase of voltage.

Though it is feasible to build alternators for almost any desired voltage, yet this consideration of space factor has limited the voltage to which it is desirable to go, to about 11,000 volts, and though alternators have been built and successfully operated at double this pressure, yet it is probably just as cheap to use transformers to step up to the higher voltages which may be necessary for long distance transmission, rather than generate such higher voltages in the alternator armature, for it must not be forgotten that the extra insulation means extra expense, and the lower space factor of the armature slot has the effect of increasing the dimensions of the whole machine.

E.M.F. OF ALTERNATORS.

The frequencies for which modern machines have to be built vary from 25 cycles for power transmission to 50 cycles for the ordinary machine for supplying current for general purposes (due, as we have mentioned, to the fact that though 25 cycles is suitable, and in many cases preferable for motors, yet 50 cycles is necessary for steady lighting), the number of poles which the machine must have will depend entirely (after the frequency has been settled) upon the speed at which it is driven. We shall, in fact, illustrate modern types possessing as many as 62 poles for a 350 kilowatt alternator, and a turbo machine having only four poles while the output is 3,000 kilowatts. The frequency in the former machine is 50 ∿ and in the latter 25 ∿.

In the single-phase alternator the various coils are simply connected up in series, so that there is a single circuit round the armature, the ends of the winding being brought out to *two* terminals. With the two-phase winding, the windings of each phase will similarly form two independent circuits through the armature, and will be brought out to *four* terminals; but this analogy does not hold in the case of the three-phase alternator. Unlike the two-phase machine, the winding is never brought out to six terminals, but the ends of the phases are interconnected, and it is only necessary ordinarily to bring the winding out to *three* terminals, because for three-phase distribution three wires suffice, while two-phase distribution systems in general require four wires—that is, the phases are kept separate.

There are two ways of inter-connecting the phases of a three-phase machine, known as the star and mesh (or triangle) connection, shown on this page. The star connection is preferable, and is generally used in three-phase alternators as well as induction motors, though the mesh connection has some advantages, and is employed in special cases.

The point to be noticed at the moment is, that in the star connection the *voltage per phase* will not be the voltage of the machine, this being the voltage measured across any two of the three terminals of the machine.

If the voltage per phase be V, the voltage across the terminals (the rated voltage of the alternator as it is usually understood) will be $V \times \sqrt{3} = V \times 1{\cdot}73$.

With a mesh-connected alternator, however, the voltage per phase will be the same as the terminal voltage, as can be seen at a glance.

In considering the voltage generated by a three-phase alternator, it is necessary therefore to consider the *voltage per phase* and not the line voltage.

The E.M.F. induced per phase in the winding of any alternator, whether single or polyphase, will be given, subject to certain correcting factors, by the expression :—

$$E = \frac{N \times t \times n \times 4{\cdot}44}{10^8}$$

where E = the E.M.F. per phase in volts (virtual).

N = the magnetic flux from one pole in lines.

t = the number of turns of armature winding in each phase.

n = the frequency in cycles per second.

It will be observed that this expression is the same as the fundamental formula for transformers, which was deduced from elementary principles in Section VI. The formal deduction from first principles in the case of the alternator is effected in a similar, but not quite identical, fashion, though a brief consideration will show that the process of induction in the case of the alternator is very comparable to the transformer action.

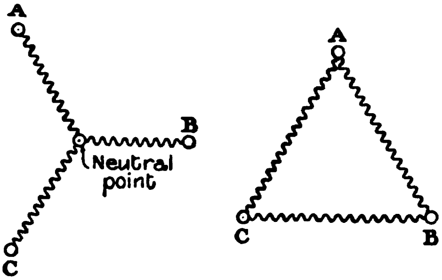


FIG. 474.—STAR AND MESH GROUPING IN THREE-PHASE WORK.

The transformer core and its windings may be compared to the alternator armature core and windings, the flux in the transformer oscillating through the core in a way in every respect comparable, as regards the induction of E.M.F. to the sweeping of the pole flux through the armature core of the alternator when at work.

This expression then, multiplied by a correcting factor, which we will call k, will give in any case the voltage set up in the armature winding if the other factors are known. We have already mentioned a cause which necessitates the use of such a correcting factor, this being that the whole winding cannot be wound completely across a pole pitch, for this would lead to a neutralising action ; and in addition to this there is the further fact, which we have not mentioned, that the formula which we have given is only correct if the alternating wave induced by the windings is truly sinusoidal (*i.e.* a sine wave). However, with the modern type of polyphase alternators, with the usual windings and usual ratio of pole arc to pole pitch (·66 being a very usual value), the correcting factor, *k*, does not differ very greatly from unity, and in such two- and three-phase alternators the value of *k* will generally be about ·95.

IRON LOSSES IN ALTERNATORS.

We have mentioned how, in direct current armatures, the core losses are found on test to be of very much greater magnitude than those given by the ordinary method of calculation for transformers. For transformers they can to a fair degree of accuracy be calculated by deducing the loss in the core by comparison with a total loss curve (hysteresis and eddy currents), obtained by actual test with a wattmeter on a sample of known weight; the readings being taken with known values of magnetic density in the core.

This method of calculation will also give very misleading results for alternators, that is to say, if the total iron loss is actually ascertained on a sample of the iron which will afterwards be used for the alternator core, it will be found that the tested core losses on the alternator core will be at least *double*, or more often *three* times the losses as measured in the sample lot of the same iron by the ordinary wattmeter method of testing. The case is better than with the armatures of continuous current machines. Mr. T. S. Allen, in the *Electrical World* of July 1st, 1905, has analysed core loss tests on a number of modern alternators, and finds that the loss as measured by the transformer method must be multiplied by a constant varying from 2·5 to 3, to give the actual loss which will occur in the completed armature.

THE POWER FACTOR.

The output of an alternator can be expressed either in kilowatts (K.W.) or kilovolt-amperes (K.V.A.). The latter is the more definite statement, as, if the output is merely expressed as a certain number of kilowatts, the statement is ambiguous to some extent. If an alternator is supplying its output to a practically non-inductive load, the output can be directly expressed in kilowatts, because the machine will then be working at power-factor unity, and the product of the volts and amperes will give the true watts. But this condition is in practical working not often fulfilled, the nearest approach to operation at power-factor unity being probably when the whole output of the machine is being dissipated in a water resistance.

In commercial test rooms the test may often be carried out by dissipating the whole of the output in water resistances, but when the machine is installed and doing its usual work it will be supplying current for lighting purposes, and also for driving motors, or for similar purposes, where the load is an inductive one.

Now it can readily be seen that if the output of an alternator is expressed merely as so many kilowatts, tested on a non-inductive load, and if the machine has to furnish this power when working on a highly inductive load, then for the same voltage the current output will be much higher. If the output of the alternator is 100 kilowatts at 1,000 volts, the current will be 100 amperes on a non-inductive load, but on an inductive load of, say, ·8-power-factor, the current will have to be 120 amperes to give 100 true kilowatts.

The result of this would be that the current density in the armature winding would be increased, and the machine would run hotter, and, as a matter of fact, it would be quite as capable of supplying the 120 amperes at power-factor unity, though the output would be raised to 120 kilowatts, and, from the manufacturer's standpoint it would be, in every way, a 120-kilowatt machine, as it would have to be just as large and expensive as if rated at 120 kilowatts.

It is therefore better to give the output in kilo-volt-amperes, and, when so rated, the machine will give the full *kilowatt* output only at power-factor unity. If the power factor is lower, the volts and amperes will be the same, but the actual kilowatts less. Very often the same end is accomplished by stating that the alternator will give so many kilowatts at a specified power factor.

Not only will a machine run hotter if it has to supply the same rated kilowatt output at a lower power factor, but the *pressure drop* of an alternator is much greater on a low power factor than on non-inductive load. This is because the CR drop in the stator winding will be greater (due to the larger current), and because of the various reactions which cause what is known generally as the inductive pressure drop.

PRESSURE REGULATION.

By pressure regulation we mean the variation in voltage at the terminals of the machine with variation of load. Obviously it is undesirable to have any great drop in the voltage when a sudden load is put on the machine. The objection in the case of lighting is obvious, and, for power work, the objection is equally great, because the torque of alternating current motors decreases roughly as the square of the applied voltage. All alternators are provided with a regulator for varying the strength of the field excitation, which enables the voltage of the machine to be restored to normal after any sudden drop has taken place; but hand adjustment of this kind is of course of very little use with sudden and frequent variations of the load. It might be thought that it would be a simple matter to use a compound winding on alternators to effect the same purpose as in a continuous-current machine; but, owing to certain differences which we cannot here go into, this problem is a difficult one, and though more or less satisfactory attempts have been made to compound alternators, yet compounding has not come into general use. To make matters worse, the pressure drop in alternators is an effect of much greater magnitude than in continuous-current machinery, where the voltage variation between no-load and full-load is generally of the order of a few per cent. and compounding is easily effected. In a given alternator the drop in volts which takes place when the load comes on, is dependent upon the kind of load under which the machine has to operate. A lighting load, consisting of incandescent lamps may cause, say, a pressure drop of 5 to 8 per cent., while, if the alternator is driving motors, *i.e.* on a highly inductive load, the drop may be of the order of 20 to 30 per cent. and drops of this magnitude are not at all unusual in commercial machines, though these figures should not be exceeded. In other words, an alternator may take a lighting or fairly non-inductive load quite satisfactorily, but, loaded with motors, this alternator may be quite worthless, the sudden switching on of a large motor producing a tremendous variation in the pressure over the whole system. We have said sufficient, then, to indicate that in alternator work the question of the pressure regulation is of supreme importance, and reference should be made to

Chapter VIII. for further treatment of the matter.

HEATING OF ALTERNATORS.

There are factors in alternator design which render the necessary dissipation of heat easy or difficult according to the circumstances, in view of the limited temperature rise of 70° to 80° Fahr. In the continuous current machine heating is practically always the limiting factor in the design. The reactance voltage can, by suitable design, *i.e.* by modification of the number of poles, the choice of a suitable winding, and by using a sufficient number of commutator segments, or by the use of commutating poles be reduced sufficiently to make the machine sparkless in running. There are, of course, special cases, such as very high speed or high voltage dynamos, in which the heating limit cannot be reached, but these cases are rare, especially since the advent of auxiliary poles. When we come to alternators, however, the case is somewhat different. Here often the pressure regulation is the limit or, sometimes, in those cases where pressure regulation is of little importance, the efficiency of the generator sets the limit, for it would be quite possible in some cases where pressure drop was unimportant to design an alternator which would not overheat, but which would have an undesirably low efficiency. The fact that the number of poles in an alternator is fixed for a given frequency and speed, often leads to a great difference between the alternator and the continuous current machine. Take a 50 ∿ alternator for, say, 200 kilowatts, designed for coupling to a slow speed engine running at 94 revolutions per minute. This machine will have 64 poles, and in order to accommodate this large number of poles, we should have to make the diameter great, and as the output of the machine is comparatively small, the axial length of the armature might not be more than a few inches. Such a machine as this would be able to dissipate a considerable percentage of 200 kilowatts without overheating, owing to the large cooling surface provided and the fanning action of the large flywheel.

In other cases the permissible pressure drop decides the dimensions of the machine, and thus, in the case of some alternators having many poles and armatures of very large diameter, it comes about that in order to keep within the limits of efficiency and pressure regulation, advantage cannot be taken of the economy of material ordinarily resulting from working up to the temperature limit. Another point in this connection is that it is frequently necessary to provide for a large amount of stored energy in the flywheel in order to ensure good parallel running, and the diameter of the field is often purposely increased solely in order that the flywheel may, when running at its normal speed, have stored up in itself the requisite amount of kinetic energy.

PARALLEL RUNNING OF ALTERNATORS.

It is often necessary to run two or more alternators in parallel so that the machines jointly may supply power to the same bus bars. Continuous-current machines, either shunt or compound, give very little trouble when paralleled if of similar size and characteristics, but in the case of alternators the conditions are more complicated, and with a given combination of unfavourable circumstances, even with identical machines, great trouble may be experienced in obtaining satisfactory parallel running, and in extreme cases it may be impossible. Alternators to run in parallel must obviously be running at the same frequency, as it is, of course, impossible to impose upon a single circuit fed by two machines, two different frequencies, or, in other words, two separate series of waves differing in frequency.

Consider two direct-coupled alternator sets, each alternator having its own engine, and it is intended to run the two alternators electrically, but not mechanically, coupled together.

It is obvious that the speed of an engine, though fairly easily controlled, could not by any type of mechanical governor be sufficiently accurately adjusted to a definite speed to enable it to keep time *exactly* with the speed of a second engine driving a second alternator which it is desired to parallel with the first.

It is absolutely necessary that the voltage waves of the two alternators should exactly coincide, otherwise there would be heavy cross currents, or as they are frequently called, synchronising currents, flowing between the two machines. The fact is, these cross currents which flow between the two alternators when they are thrown in parallel, if they are not quite in synchronism *tend* to pull the machines completely into step provided the difference in phase when the machines are coupled together is not too great. This results from the fact that the machine which is just in advance of the other tends to drive it as a motor, and the other is accelerated while the former is retarded.

In practice some form of instrument for indicating the exact moment of synchronism is employed. As long as only a slight difference of phase exists when the alternators are coupled together, the cross currents will automatically bring the machines into complete synchronism ; but if the difference of phase is great when the machines are coupled together, the tendency will be to pull the machines into complete opposition of phase, which means a short circuit, which will either damage the machines or will pull the engines up.

The actual details of the operation of synchronising two alternators are described elsewhere, as are also the various types of synchronisers actually employed, and we will therefore briefly consider how the capacity of an alternator to run in parallel with another is affected by the design, and mention certain devices which are employed to secure immunity from paralleling troubles.

Two alternators running in parallel, or, in fact, the running in parallel of any synchronous machinery, may be roughly compared to the action of two flywheels running side by side with their shafts in line, and with a spring coupling interposed.

When the speed of rotation is uniform, and both flywheels running at the same speed, no strain will be exerted on the coupling. Suppose that the springs of the couplings are susceptible to both tension and compression, and it will then be obvious that if a brake is applied to one flywheel, causing it to momentarily slow down, a pressure will be exerted on the spring coupling, and the spring being compressed, will then exert a torque tending to restore the flywheels to the position of equilibrium of the spring. There will thus be a tendency for the wheels to oscillate until the normal conditions are restored, that is, until the spring is neither in tension or compression. This is analagous to the "hunting" effect which occurs when two alternators are running in parallel, or when an alternator is driving another alternator as a motor (*i.e.* a synchronous motor). The same thing occurs with a rotary converter, which is really a synchronous motor, and if the hunting is violent it not only leads to heavy surges or cross currents between the machines, but they may eventually fall completely out of step.

The equivalent of the brake which we have imagined applied to one of the two flywheels is, of course, a difference in load or a sudden variation in the engine speed

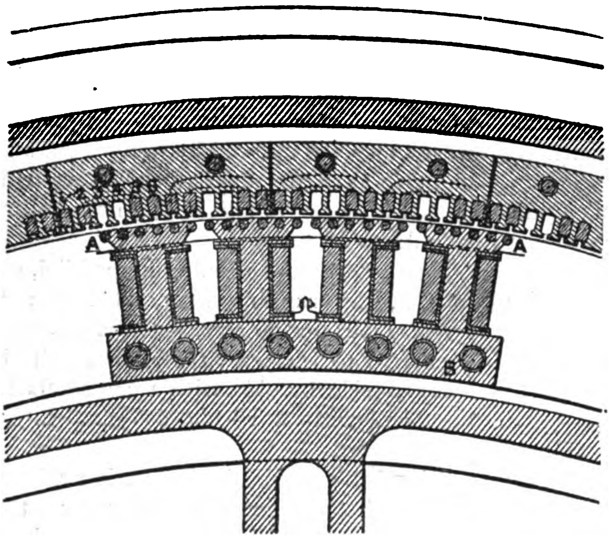


FIG. 475.—HUTIN-LEBLANC AMORTISSEURS IN POLE FACES.

in the case of two alternators running in parallel.

In reciprocating steam engines or gas engines, the turning effort (in one revolution) varies slightly. In a simple gas engine there is only one impulse in the cylinder every two revolutions, and in consequence heavy flywheels are generally employed, but such driving is very unfavourable to good parallel running of alternators.

The ordinary compound or triple expansion steam engines are much better, and the steam turbine, in which the turning moment is perfectly uniform, is the best of all for good parallel running.

We see now why, as we have mentioned, it is frequently necessary to have great weight in an alternator flywheel rim, merely in order to decrease the irregularity of angular velocity due to the irregular turning moment of the engine, which is commonly described as the "cyclic irregularity."

But by careful attention to the electrical design a good deal can also be done, for, by making the self-induction of the armature great, there will be a tendency to prevent sudden variations in the armature current, and thus to prevent *sudden* surges of current between machines tending to pull out of synchronism.

Modern alternator armatures possess greater self-induction than the type of armature very common a few years ago, in which there was no iron revolving, for example, the Ferranti and other types of disc armatures consisting merely of coils of copper strip with no iron core.

Another means employed to prevent hunting is to use "damping" coils or "amortisseur" windings, which usually take the form of short circuited copper grids embedded in the pole faces of the machine, or in some cases of grids of copper or bronze placed between the pole tips. Fig. 475 shows a Hutin-Leblanc alternator fitted with such damping coils embedded in the pole faces, while Fig. 476 shows the interpolar type fitted to a machine by the British Westinghouse Company, Limited.

Messrs. Bruce Peebles and Co., build their laminated pole tips with cast copper end pieces, and instead of riveting the tips with steel rivets as for direct-current machines, they make about three-quarters of the rivets of drawn copper rod, thus at the same time securing the tips and providing a damping circuit.

Any sudden variation in the armature current will produce a variation in the magnetic flux through the magnetic circuit, and thus set up eddy currents in the damping coils, and, as we have already seen, such currents tend by reaction to prevent sudden change in the value of the flux through the circuit.

The alternators which we shall now describe are all of considerable size, as there is little demand, beyond experimental machines, for alternators of small outputs.

An excellent example of armature construction by Messrs. Vickers, Sons and Maxim, Limited, is illustrated in Fig. 477. This is a three-phase machine 428 revolutions per minute, having an output of 300 kilowatts at 200 volts, built for the East Indian Railway. Though it is a three-phase alternator, it will be noticed that the winding is brought out to *four* sweating thimbles, and the explanation of this is that it has been necessary to bring out the common junction of the three phases for the purpose of earthing, which is quite common practice.

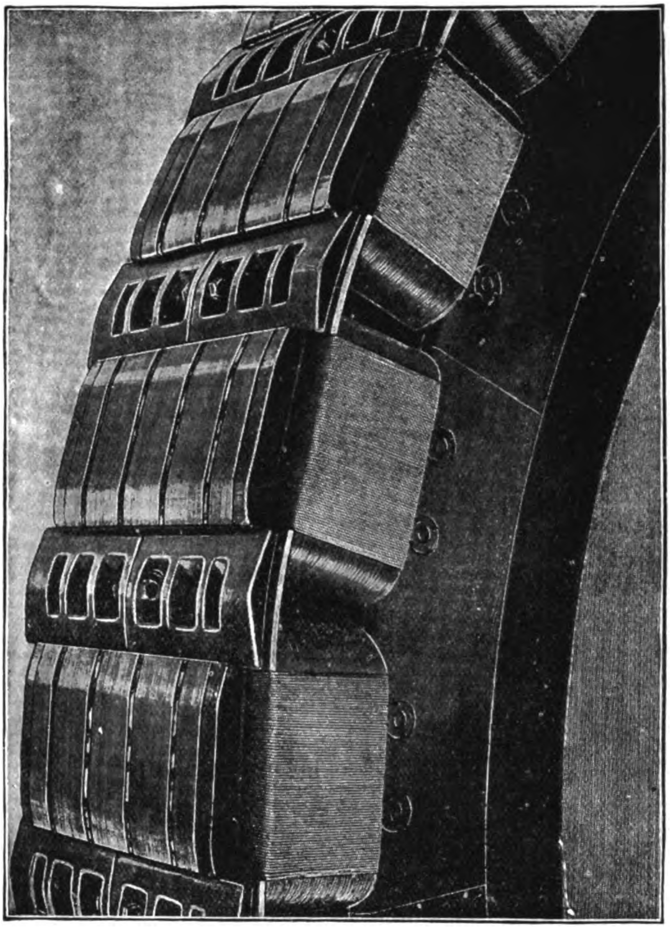


FIG. 476.—INTERPOLAR DAMPING CIRCUITS ON A REVOLVING FIELD MAGNET.

The armature frame is of cast iron in the very usual box construction, allowing ample ventilation through the cored holes in the casting, and the cast iron segmental end shields are also provided with ample ducts ; there is, however, only one radial duct through the actual armature core, while in most modern alternators we find considerably better ventilation. The axial length of the core, however, is not great.

The winding is of the double coil type, that is in two ranges, and there are 144 slots, or 4 slots per pole per phase. As there are 12 poles there are thus 36 coils in all, each coil being wound in 8 slots. The coils are former wound, the slots being completely open, and after the coils have been placed in position in the slots, they are securely held in with teak wedges.

It will be noticed that one of the straight coils on the right of the photograph has not been placed in position, and for a very obvious reason : that, as the frame is split, this coil and the corresponding one on the left side can only be put in when the two halves of the frame are put together.

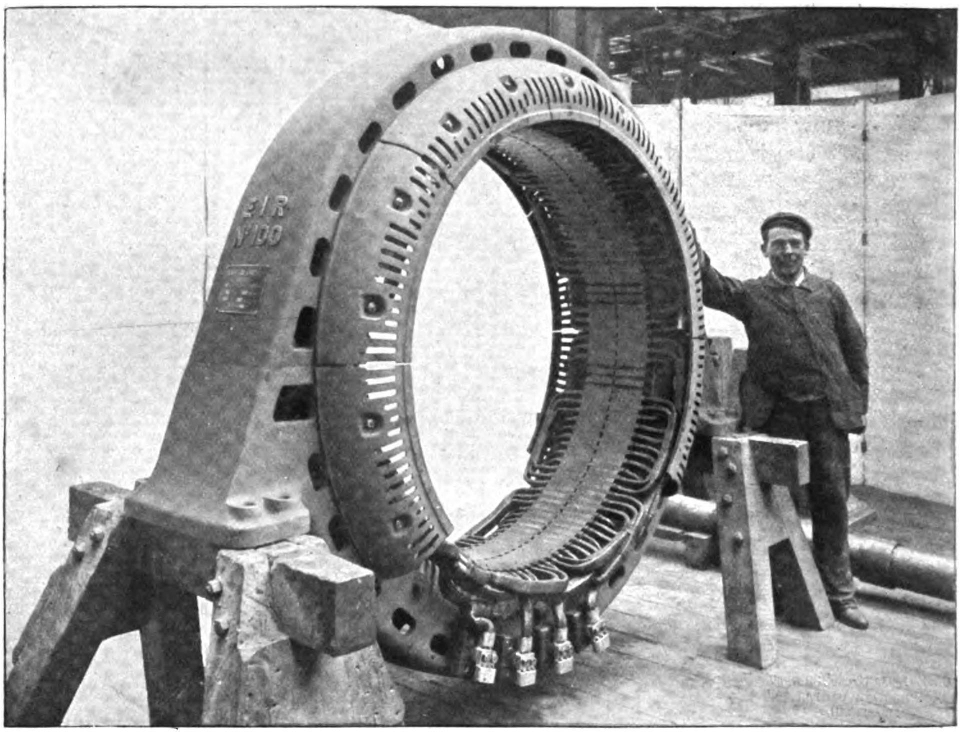


FIG. 477.—THREE-PHASE ARMATURE (FIELD REMOVED) BY VICKERS, SONS AND MAXIM.

An alternator frame of this size would generally be packed at the makers' in two cases, and the remaining coils placed in position only when the machine is finally erected. In such a case former-wound coils are very convenient, as otherwise the services of an armature winder of some experience would have to be requisitioned to put in the last few coils on the spot if hand-wound coils and closed slots or partially closed slots were adopted.

An alternator of similar design mechanically, by the Lancashire Dynamo and Motor Company, Limited, with direct coupled exciter, is illustrated in Fig. 478.

This is a 12-pole machine 3-phase, 300 revolutions per minute at 30 ∿, giving an output of 400 kilowatts on a ·8 power factor. The exciter is hung from the pedestal bearing in a very neat and ingenious way.

A sectional view and end elevation of a standard U.R. type alternator with direct coupled exciter, by Messrs. Siemens Brothers Dynamo Works, Limited, is shown in Fig. 479. One pedestal bearing is shown, the standard practice with direct driven sets, and the exciter is mounted on a footplate bracketed out from the bearing.

A photograph of the field system of the same standard machine is shown in Fig. 480. The poles, of mild steel bar of circular section, are bolted to a cast steel flywheel of very neat design, and the pole tips are laminated and held on to the poles by four set screws. In the field system, illustrated, the winding is of copper strip wound on edge, and presenting a clean metallic surface

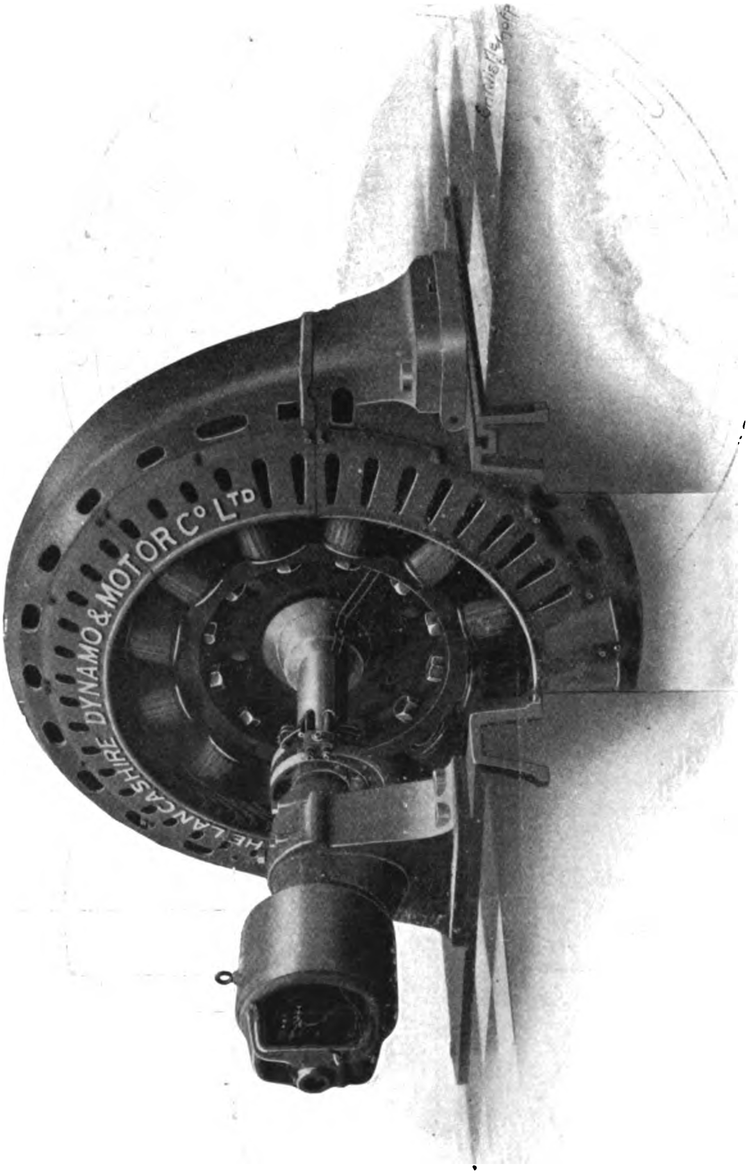


FIG. 478.—THREE-PHASE ALTERNATOR, WITH OVERHUNG EXCITER, BY THE LANCASHIRE DYNAMO AND MOTOR COMPANY.

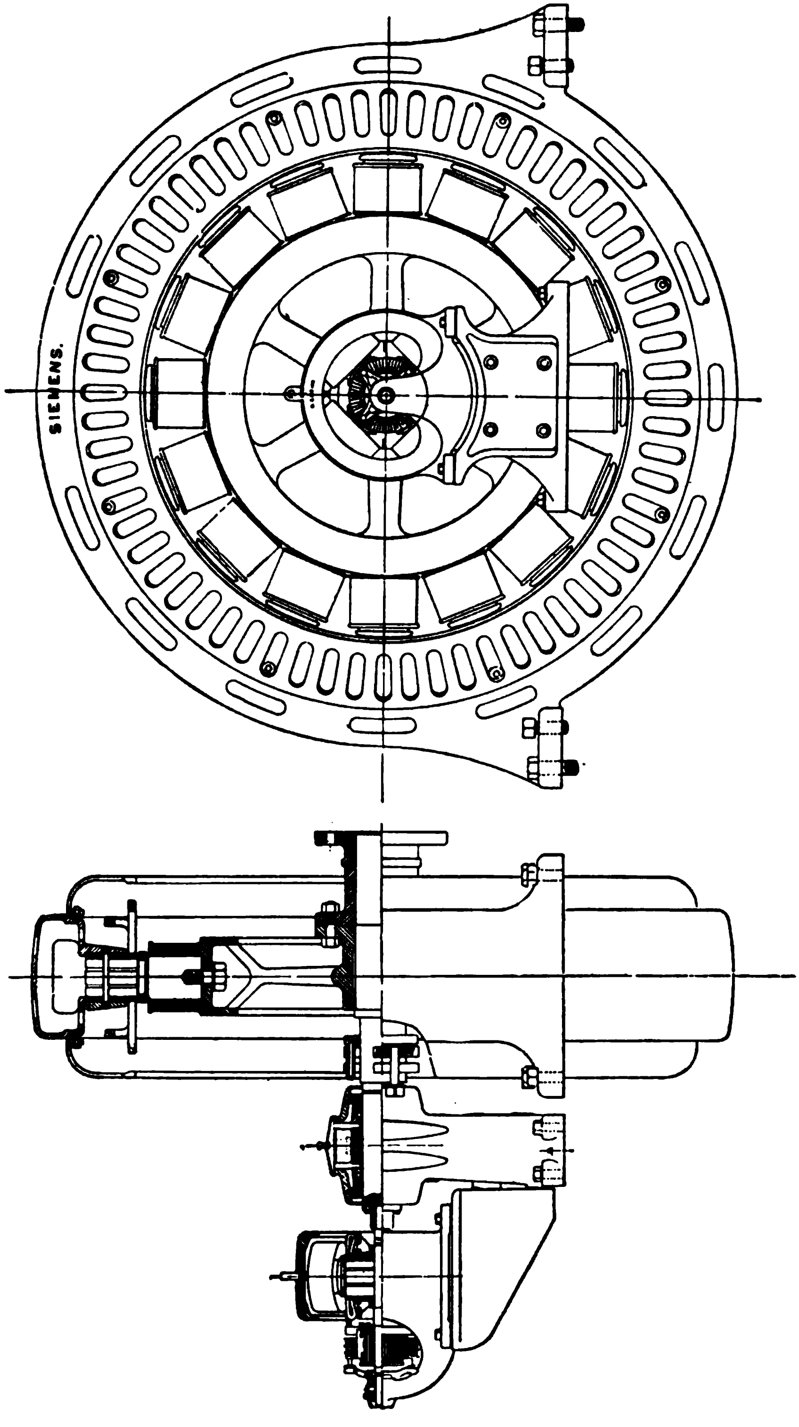


FIG. 479.—CROSS SECTION AND ELEVATION "U.R." ALTERNATOR, WITH DIRECT-COUPLED EXCITER, BY SIEMENS BROTHERS.

on the outside, which is very effective in cooling the field coils. It is always good practice to employ such edgewise strip when it is possible, but often the section of copper required for the field winding is such that (due to a certain excitation voltage being specified) the resulting size of strip would be thin and awkward or impossible to wind, and then a flat strip winding must be resorted to.

In addition to better cooling and a better utilisation of the space available for winding (a higher "space-factor") the edgewound strip possesses the advantage that the centrifugal forces which are brought into play when the field is revolving are resisted in the best possible way, and there is not the tendency with the edgewound strip for the winding to creep radially, which must always be guarded against with a flat strip winding.

In the small machines in this standard line the armature frame is cast in one piece; in the larger sizes it is cast in either two or four pieces, held together by concealed bolts, which are, nevertheless, readily accessible. In all cases the armature plates are clamped by means of insulated through bolts, between cast iron flanges, one of which is cast solid with the frame, the whole core being built against a surface turned in the stator frame.

The core is built up of laminated stampings insulated on both sides; the slots are open, with grooves to receive wooden keys or wedges for holding the coils firmly in place. The former-wound coils, illustrated in Fig. 481, are insulated with mica, moulded on to the straight part, and the tube of mica when the coil is in position projects beyond the armature core to such a distance as to prevent leakage.

The ends of the coil are taped with special oiled tape, and being very rigid

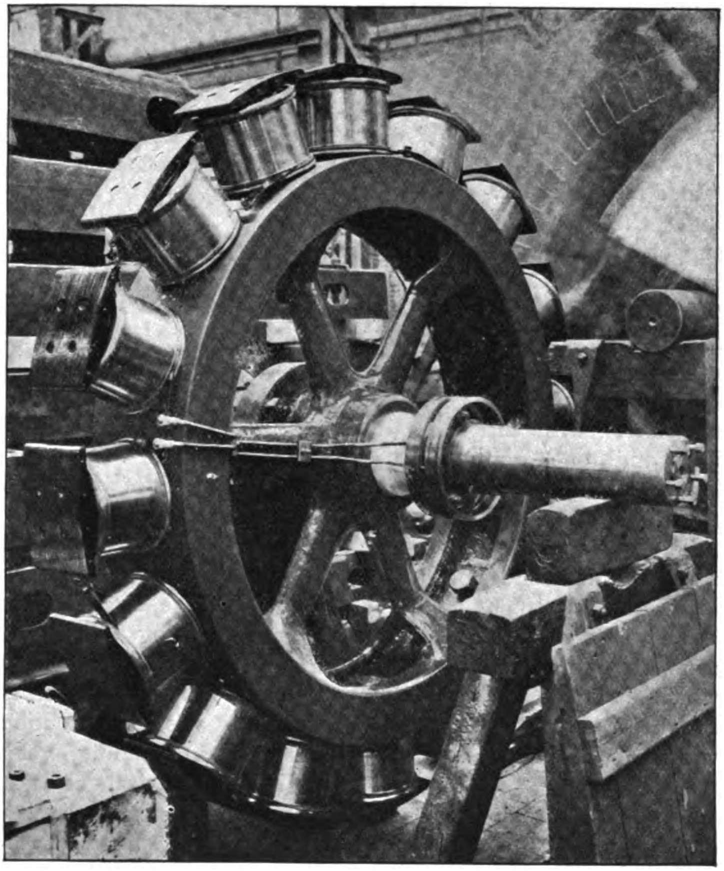


FIG. 480.—MAGNET WHEEL OF MACHINE SHOWN IN FIG. 479.

they keep well away from all parts of the frame or core, and thus have ample air insulation, they are thoroughly protected by the shields on the frame and do not interfere with ventilation.

Messrs. Bruce Peebles and Co., Limited, list machines in standard sizes up to an output of 1,000 K.V.A. at 214 revolutions per minute and 25 ∿, this being a 14-pole machine; or 1,250 K.V.A. at 150 revolutions per minute for 50 ∿, this being a 40-pole generator.

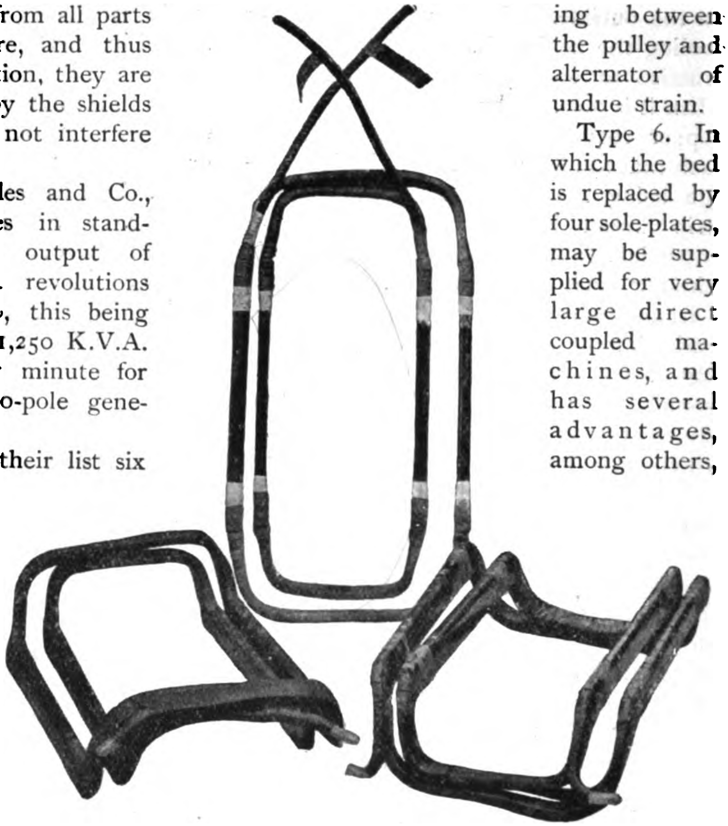


FIG. 481.—FORMER-WOUND COILS AS USED BY MESSRS. SIEMENS BROTHERS AND CO.

They enumerate in their list six driving arrangements for alternators, which we quote as being of interest :—

Type 1. Self-contained machines, having the bearings supported in end brackets bolted to the frame ; these are suitable for outputs up to 300 K.V.A.

Type 2. Open type alternator with no bed and one outboard bearing for direct coupling to engine.

Type 3. Open type alternator with short "U" bedplate and one bearing, also for direct coupling to engine.

Type 4. Open type alternator with complete bedplate and two bearings, which may be driven either by direct coupling to the engine (preferably with a flexible coupling) or by belt or rope.

Type 5. More desirable for belt or rope driving, as, in this case, the bedplate is extended and a third bearing added outside the pulley, thus giving additional support to the shaft and relieving the bearing between the pulley and alternator of undue strain.

Type 6. In which the bed is replaced by four sole-plates, may be supplied for very large direct coupled machines, and has several advantages, among others, those of being convenient in erection, and also economical.

The armature laminations are, if above 75 K.V.A., arranged in segments, alternate segments breaking joint, thus ensuring minimum resistance to the field flux. The slots are almost closed in form, as it is found that, although this construction entails more labour in winding, yet it affords much better electrical characteristics with the form of field magnets adopted. The slots are lined with insulating tubes of composition, varying according to the voltage to be adopted, but, in general, the insulation consists of pure mica, mechanically protected by thicknesses of presspahn.

An example of high tension three-phase winding is shown in Fig. 482, this being the armature of a 1,500-kilowatt, 10,000-volt machine. This is a hand-wound wire winding, and the ample ventilating ducts should especially be noticed.

The field magnet wheels are of cast iron or steel, depending upon circumstances, and solid steel poles and laminated pole tips are used. The individual turns of the edge strip winding are insulated from one another by special paper. A point worthy of attention in these alternators, which has been adopted by this firm in common with other manufacturers, is the use of steel slip rings, these being found to give good results with soft carbon brushes.

An elevation, with the details of pole construction shown in section, and a complete half sectional view of a type of flywheel alternator, manufactured by Messrs. Dick, Kerr and Co., Limited, is shown in Fig. 483. In this design, the whole mass of the poles is of laminated iron, this entire lamination being an excellent feature, as, with solid poles, even if laminated tips are used, eddy current losses occur in the pole, due to the armature reaction causing variations in the field flux.

This construction, with dovetailed laminations fixed on to the flywheel rim by means of cast iron flanges, makes an excellently ventilated design, as ducts are provided right through the field system, corresponding with the ducts in the armature core.

We shall presently describe further examples of machines by this well-known firm in connection with turbo-alternators.

The Electric Construction Company, Limited, of Wolverhampton, have kindly given photographs and drawings of two of their recently built large polyphase alternators.

The first machine is a two-phase generator of 1,500 kilowatts supplied to Leeds Corporation, and is shown by a photograph in Fig. 484. The flywheel rim is exceedingly massive, to meet specially stringent conditions necessary for good parallel running. The direct coupled exciter is supported on a bracket bolted to the main bedplate, and the machine is complete with two bearings, a rather unusual feature in a generator of this size; barring gear, which can be hand operated from both ends of the bedplate, is used for sliding the stator laterally for inspection or repairs. An interesting point in connection with the exciter is that it has no end bearing, the exciter armature being built direct upon the main shaft.

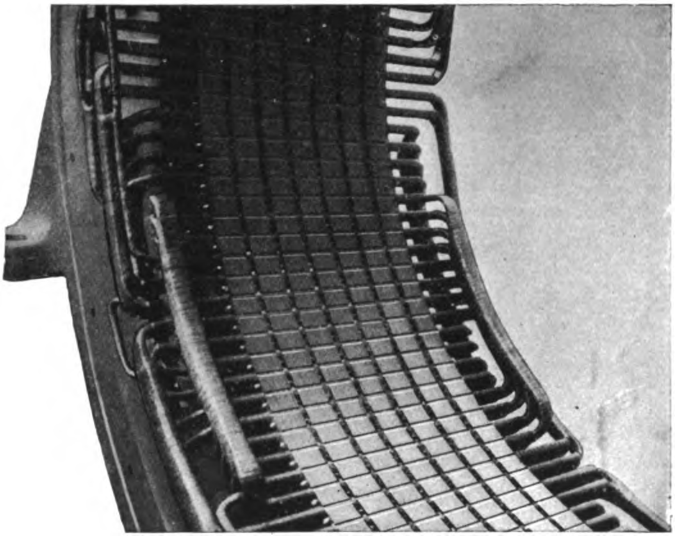


FIG. 482.—ARMATURE WINDINGS OF HIGH-TENSION THREE-PHASE MACHINE.

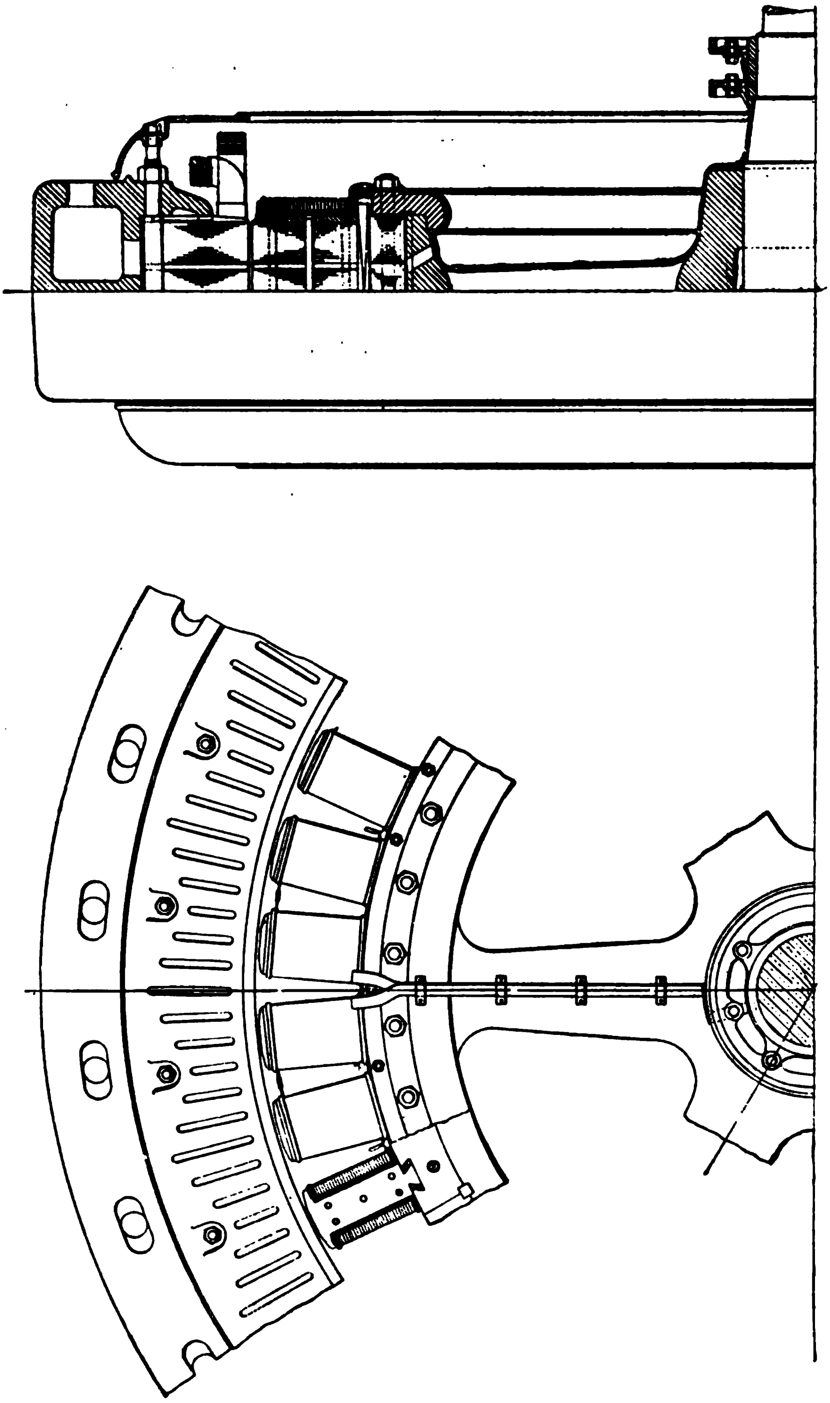


FIG. 483.—CONSTRUCTION OF MAGNET WHEEL HAVING LAMINATED RIM AND LAMINATED POLES.

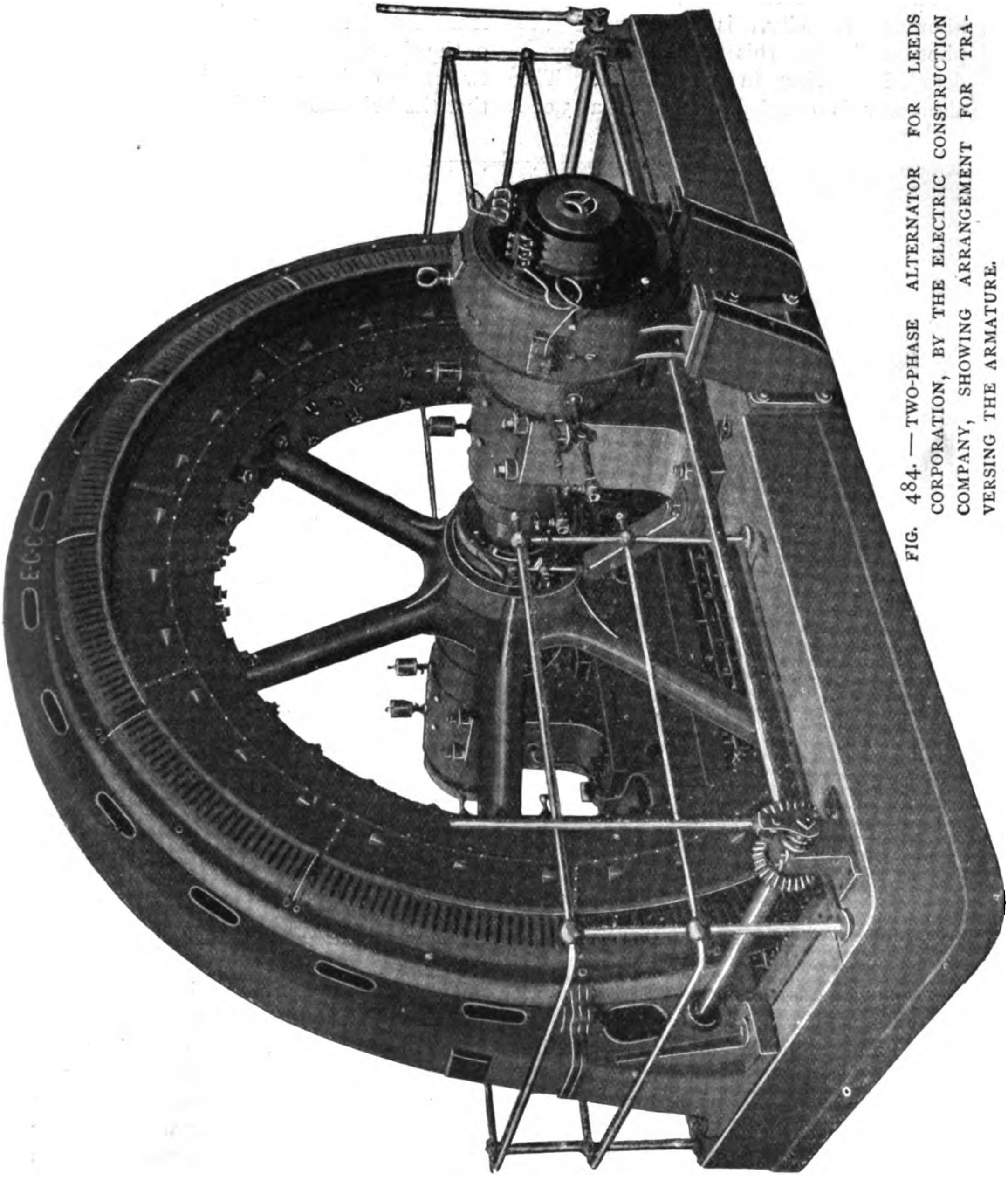


FIG. 484.—TWO-PHASE ALTERNATOR FOR LEEDS CORPORATION, BY THE ELECTRIC CONSTRUCTION COMPANY, SHOWING ARRANGEMENT FOR TRAVERSING THE ARMATURE.

A much larger alternator, supplied to the Greenwich station of the London County Council tramways, and of 3,000 kilowatt capacity, is shown by the photograph on this page, and by a detailed drawing in Plate VIII. The alternator is coupled direct to a 5,000 horse-power engine, and gives three-phase currents at 6,600 volts (3,820 volts per phase) and 25 frequency, the speed thus being 95 revolutions per minute with 32 poles.

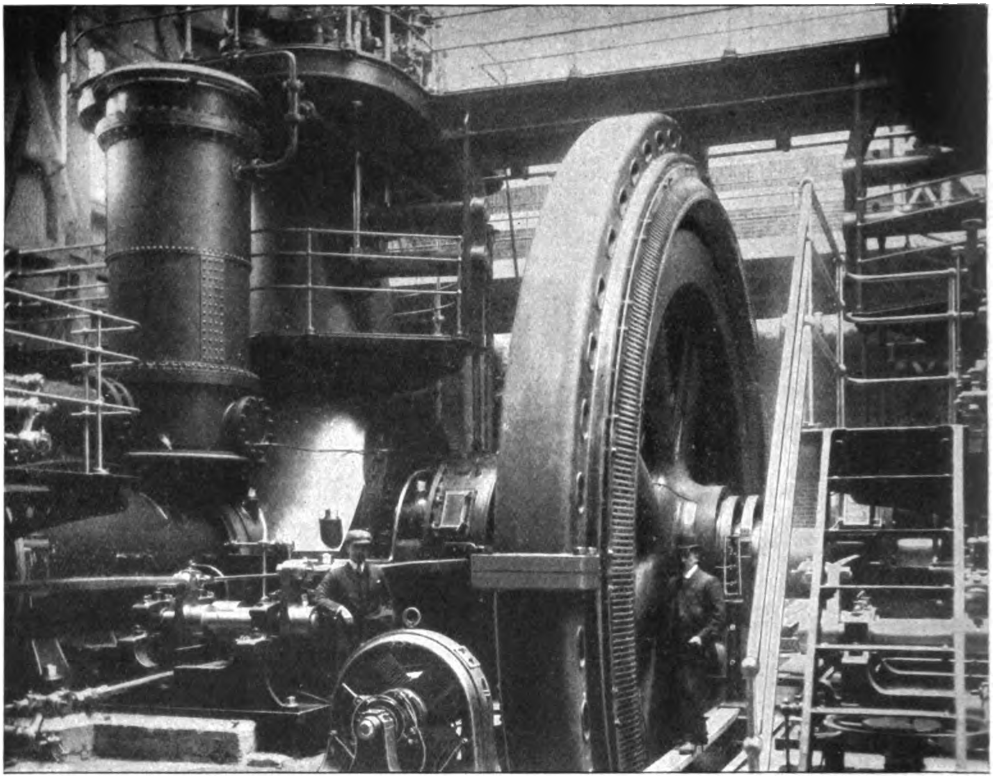
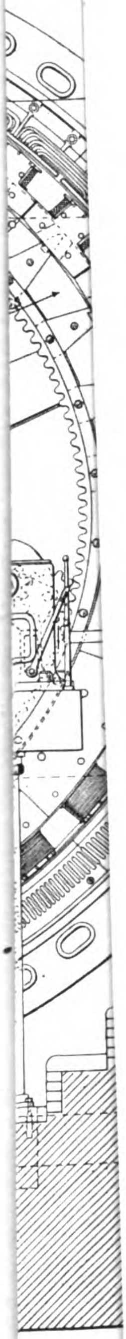


FIG. 485.—5,000 HORSE-POWER THREE-PHASE GENERATOR FOR TRAMWAY WORK DIRECT COUPLED TO CROSS-COMPOUND ENGINE, INSTALLED AT GREENWICH.

The magnet wheel of this generator presents some interesting features. The main casting is rather over 23 feet in diameter, and has eight arms. This wheel was cast in four pieces with two arms in each section, but in order to avoid stresses in the material and to allow for proper shrinkage, it was found necessary to cut each section of the rim at the middle of its length between two of the arms. The result was that the hub was made in four pieces, each piece having two arms projecting from it, but the rim really consisted of eight independent segments. At each of the outside ends of a segment the surface was properly faced, so that at these four points the segments came together with properly faced joints, but where the segment was divided between two arms, no such facing could be effected. The keying together of



ECTRIC CO

to
ield
ure
the
ure
in
the
ne-
ed,
the
ter
he
of
ob-
ri-
at
he

F
R
R
H

A
the
Cou
kilo
pho
det
alte

F

hc
cu
ph
be
pc

se
ca
ar

the segments was effected by turning a circular groove in the face of the rim, as is clearly seen in Fig. 486, so as to leave a pin, half of which is formed of metal in one segment, and the other half in the neighbouring segment. A steel ring was then shrunk over the pin thus formed, securely keying the two sections of the rim together. This was done at each of the four faced joints, but at the other four dividing cuts a 2 inch hole was drilled, as is clearly seen in the upper half of Plate VIII. and also in Fig. 486, and into the hole a 2 inch steel bar was fitted. A ring and pin was formed at this break in the same manner as at the four faced joints, only instead of drawing the parts into contact the tension in the ring pulled the two portions hard against the steel bar. At the hub the four quadrants are secured together by steel rings shrunk on to a turned recess, one on each side of the hub. These rings are seen most clearly in section in Plate VIII. The rings securing the segments of the rim together are also seen in section at the top of the same view, and again in three places in the left hand view of the same plate. After the parts had been secured together in this manner, the periphery was slotted with dovetailed slots for the reception of the pole stampings, and when these had been placed in position the outside plates seen in section at the top of the right hand view of Plate VIII. were fixed, four on each side of the wheel. These were of boiler plate, each 1 inch thick, and were riveted in position as is shown in Fig. 487, and everything turned in position as seen in Fig. 488. An internal tooth rack is fitted all round the inside of the flywheel rim for the barring gear, being secured to the rim by bolts. The pulley for the rope driving of the exciter is separate from the flywheel, and is mounted by its side on the shaft. The plate shows a section in one quadrant through the centre of the flywheel rim exposing the ribs, which serve as distance pieces to form a ventilating duct through the field magnet core. The section of the armature in that quadrant is partly through the corresponding vent plate in the armature core and partly through the plane in which are the end vent plates. In the upper right-hand quadrant the framework is shown with end shields removed, while the magnet wheel is seen with the pole cores in position, but with the outer end plates of boiler plate removed. The main function of so great a thickness of boiler plate (4 in. on each side) is probably to provide strength to resist centrifugal force, since cast iron is somewhat unreliable under such conditions. The

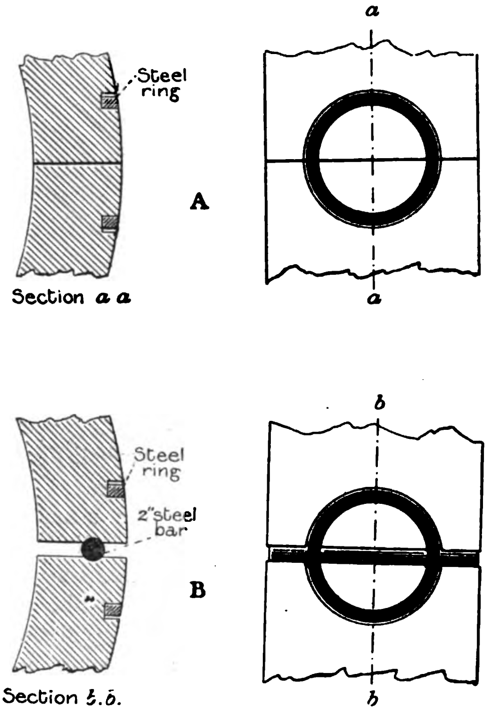


FIG. 486.—UPPER VIEW SHOWS METHOD OF KEYING THE FOUR SEGMENTS; LOWER VIEW SHOWS METHOD OF KEYING OVER CONTRACTION CUT IN CENTRE OF EACH SEGMENT.

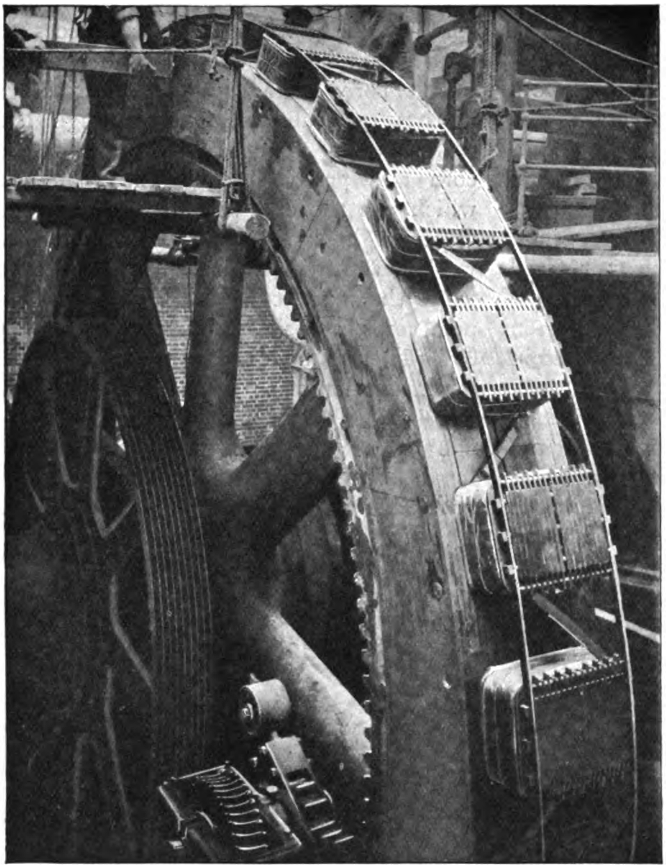


FIG. 487.—MAGNET WHEEL OF GREENWICH GENERATOR; SIDE PLATES BEING RIVETED ON; FIELD COILS IN POSITION.

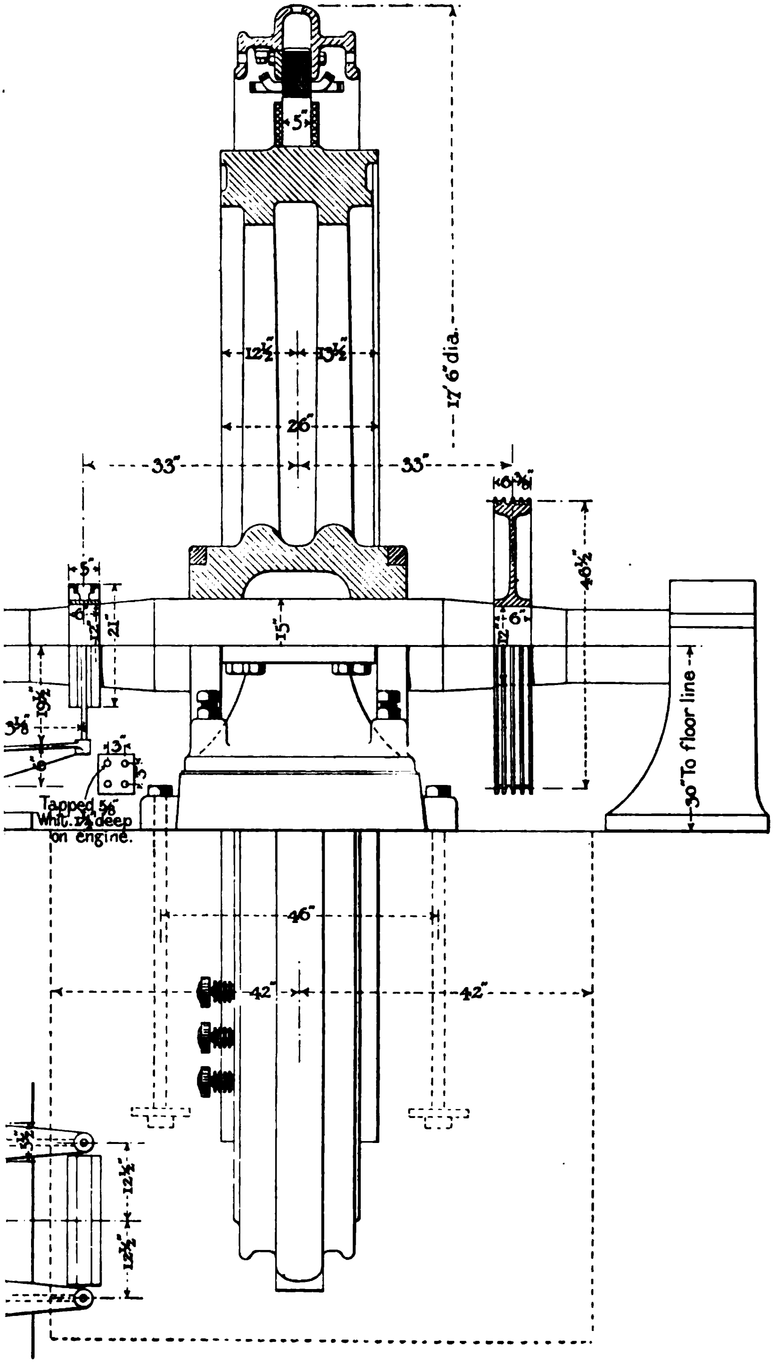
pole cores obviously require very little to hold them against lateral shifting.

The over-all diameter of the armature frame is 29 feet, and for this large diameter very massive construction is necessary to maintain rigidity. The frame is a liberally designed box structure, the core segments being dovetailed into the housing, and arranged to give five ventilating ducts in a gross core length of about 19½ in., or a duct pitch of about 3¼ in.; and there is also one duct running through the field corresponding in position to the centre duct in the armature core. So excellent are the cooling arrangements that continuous overloads are easily taken, the author having seen the machines delivering 4,000 kilowatts for hours together without the least improper heating. The armature winding is of the double-coil type, there are thus $32 \div 2 = 16$ coils per phase, or 48 coils in all, half bent and half straight, and each coil is wound in 10 slots, there being thus $10 \times 48 = 480$ slots in all, each slot being 2⅛ in. deep by ⅞ in. wide, that is there are five slots per pole per phase.

A specially interesting feature is the motor-driven barring gear; the motor is shown in the foreground of Fig. 485, the illustration of the alternator erected at Greenwich. The barring motor is coupled to a transverse shaft running into a gear box, whence the drive is transmitted to a pinion gearing to teeth on the inside at the flywheel rim.

The exciter is rope driven from the main shaft, and is one of this firm's standard six-pole continuous current generators.

A large flywheel alternator three phase 350 kilowatts on a power factor of ·80 (therefore 440 K.V.A.), by Messrs. Johnson and Phillips, Limited, is shown in Plate IX. The speed is 97 revolutions per minute for 50 ∿, at 1,000 to 1,100 volts pressure star connected, and the number of poles is 62. The remarkable feature of this machine is the relatively very large



CTOR RINGS
brush supports.

ILLIPS, LIMITED. (*See page* 542.)

diameter of armature and short core length. This, we understand, was rendered necessary by the difficult conditions. The machine had to run perfectly in parallel with others, and therefore demanded a large flywheel effect, which was provided for by a great mass of metal and a large diameter of fly-wheel. This alternator is installed at the Lowmoor Ironworks, where it is used for motor driving. The exciter is of Messrs. Johnson and Phillips' standard type, its voltage being 220.

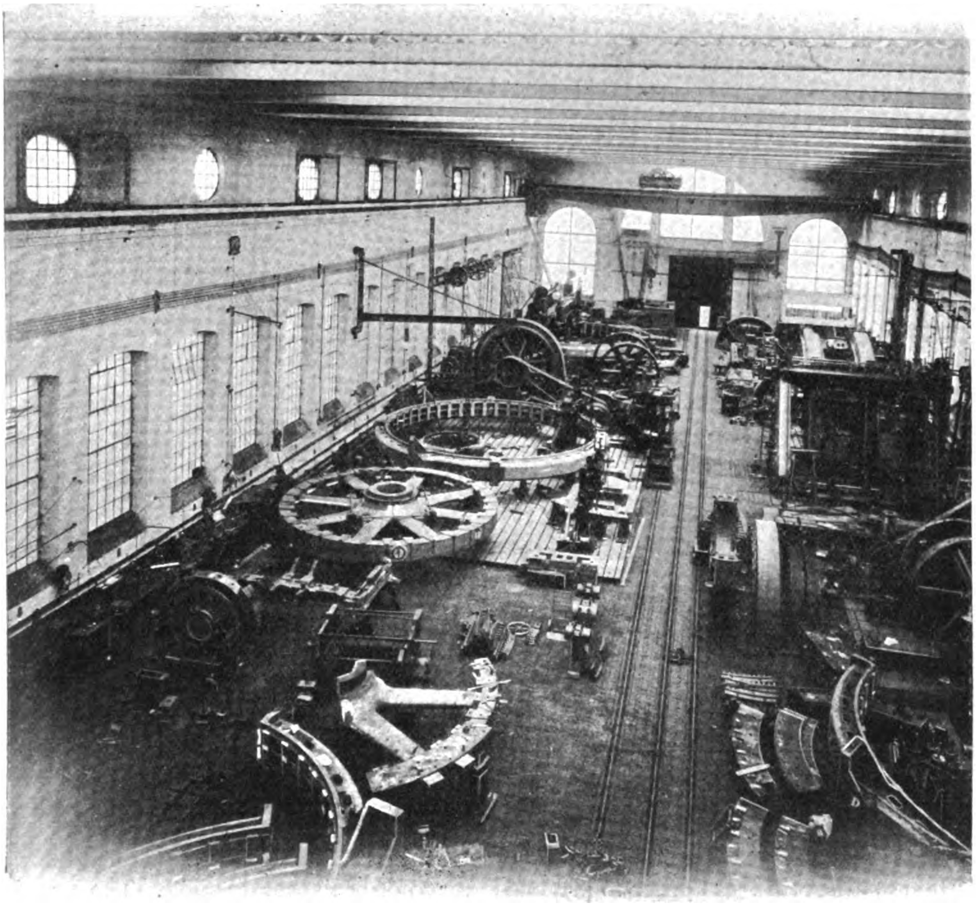


FIG. 488.—CASTINGS OF GREENWICH MAGNET WHEELS PREPARED FOR KEYING AT THE RIMS.

BROWN-BOVERI ALTERNATORS.

On page 545 are illustrated some alternators recently constructed by Messrs. Brown, Boveri and Co., which possess features of interest. The machine shown in Figs. 490 and 491 is installed at Venice at the Cellinoe Generating Station. The machine

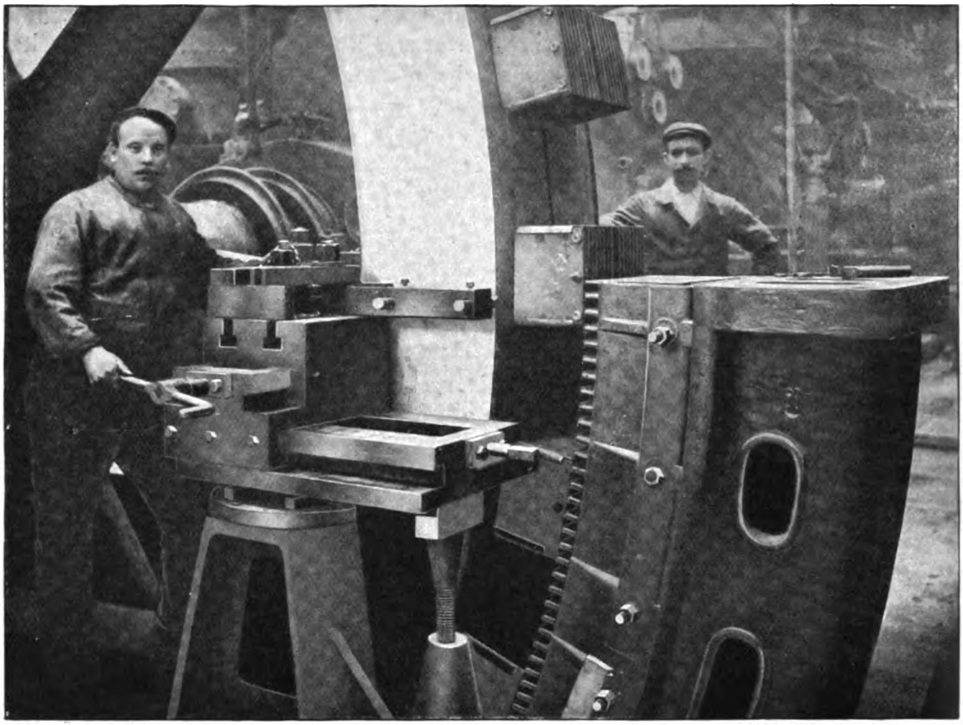


FIG. 489.—MAGNET WHEEL OF GREENWICH GENERATOR IN COURSE OF ERECTION.

has an output of 2,600 horse-power at a voltage of from 3,600 to 4,800 volts, and runs at 315 revolutions per minute. The poles are secured to the rotor hub by bolts passing through the cores from the pole face inwards, not, as is frequently done, through the rim of the hub into the bottom of the cores. In order to produce so high a voltage at this low speed, and at the same time to avoid a large diameter, an unusually long machine is employed, as may be best seen from Fig. 490. This view shows the stator without the end shields, and it will be further noticed that the armature may be divided into two and the top part lifted off, breaking the connections at three points on each side. The housing is well ventilated, the numerous ducts being clearly visible in the top part of the illustration, and the outlet holes in the housing on the left hand side.

An entirely different type of design is shown in Figs. 492, 493, 494. The feature of this machine is the arrangement adopted to produce a very great fly-wheel effect so that the cyclic variation of angular velocity may not be too considerable. The machine is specially suitable for coupling direct to an oil engine. The arrangement adopted is to employ a stationary armature and a rotating field, but contrary to the usual practice of rotating the field within the armature ring, the field has been provided with inwardly projecting poles and rotates externally to the armature. The construction of the armature may be well gathered from Fig. 492, where the lower half is already mounted on a hub of very

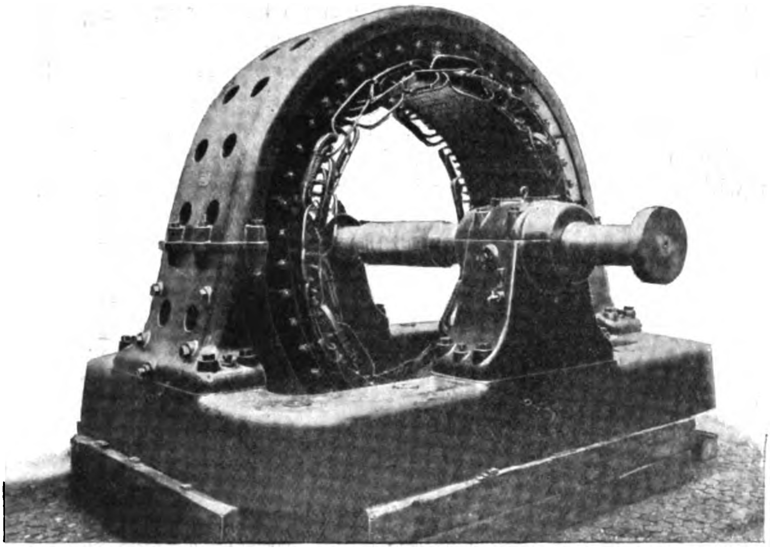


FIG. 490.—THREE-PHASE GENERATOR, 2,600 H.P. AT 4,000 VOLTS, BY MESSRS. BROWN-BOVERI AND CO.

screw being provided by a projection cast on the pedestal. When the two screws are turned, the upper half of the armature is drawn to one side, the face of the hub traversing a slideway provided for it on the pedestal. This axial displacement is shown in Fig. 492, the screw bar on the side which is visible being entirely solid construction and the upper half is in process of being slipped into position. The main armature frame consists of four cast ings, each comprising four spokes and a central hub, such that when the four portions are all bolted together an eight-armed wheel is formed, each arm really consisting of two spokes. The armature laminations are mounted on the external periphery of the rim of this wheel and carry a bar winding in slots that are to all intents and purposes closed. Two ventilating ducts are carried through the armature laminations. In order to provide for convenient inspection of the armature, two long screw bars are provided, one of which is very clearly seen in Fig. 493, the screwed portion engaging with a nut secured to the hub, and purchase for the

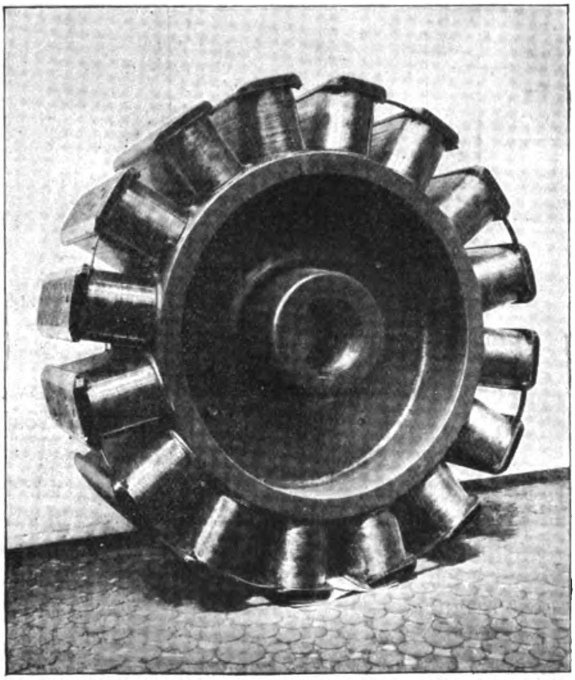


FIG. 491.—MAGNET WHEEL FOR MACHINE SHOWN IN FIG. 490.

embedded in the hub. The magnet wheel is overhung, having no spokes on the side on which these devices are found. A glance at Fig. 494 will convey a good impression of the magnitude of the flywheel effect, and also affords some view of the spokes which support the magnet wheel, these being visible on the other side of the armature. Hand barring gear is provided, engaging by pawls with ratchet teeth formed in the outer periphery of the magnet wheel. The shaft on which the magnet wheel is mounted comes right through the armature, having a bearing in the pedestal which can be seen, and carrying the exciter armature on its outer end. The shaft has no bearing at the extreme end, the exciter armature being overhung; there is, however, a small pedestal to provide a concentric bearing for the brush rocker. This can be seen in Fig. 494. When the long screws above referred to are withdrawn, the whole armature can be revolved upon the magnet wheel shaft as upon a trunnion, so as to bring the lower half of the armature to the top and so enable it in turn to be slid to one side and inspected or repaired.

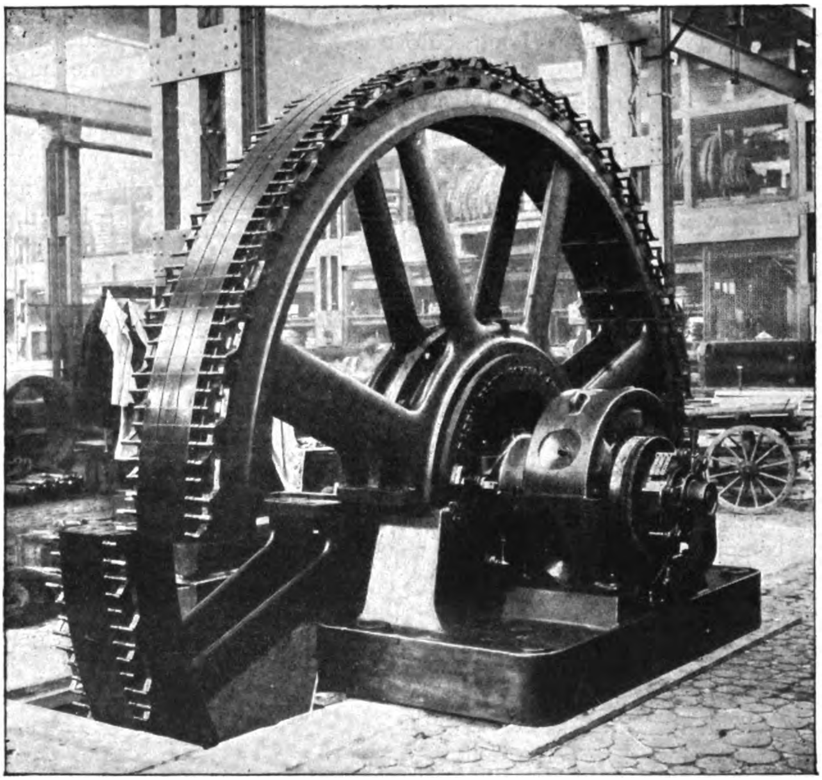


FIG. 492.—BROWN-BOVERI ALTERNATOR, HAVING EXTERNAL REVOLVING FIELD AND PROVISION FOR EXPOSING ARMATURE.

A machine for generating very heavy currents for furnace work is illustrated in Fig. 495. The construction of the rotor is identical with that shown in Fig. 491, but

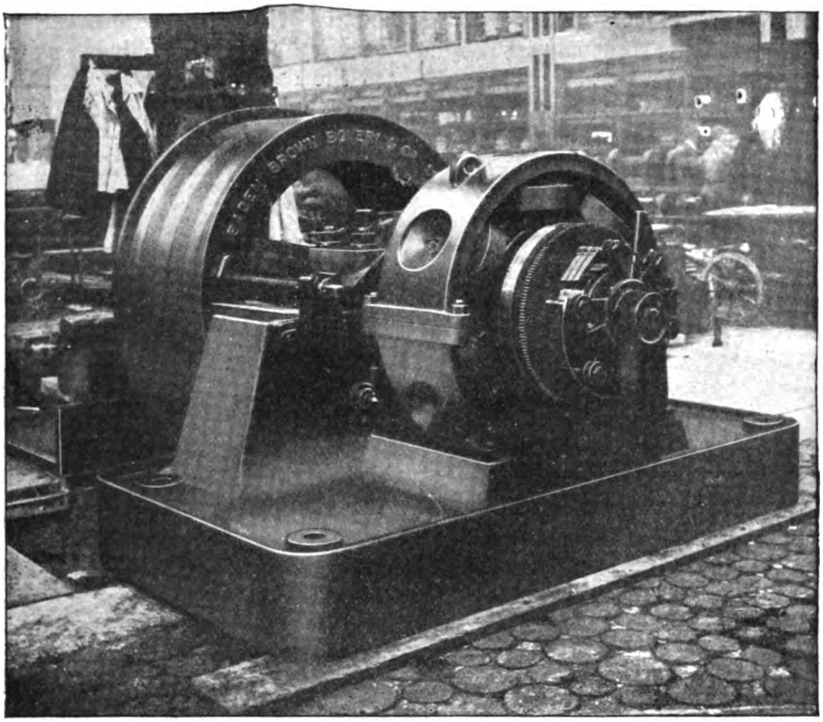


FIG. 493.—HUB AND BED PLATE OF MACHINE SHOWN IN FIGS. 492 AND 494.

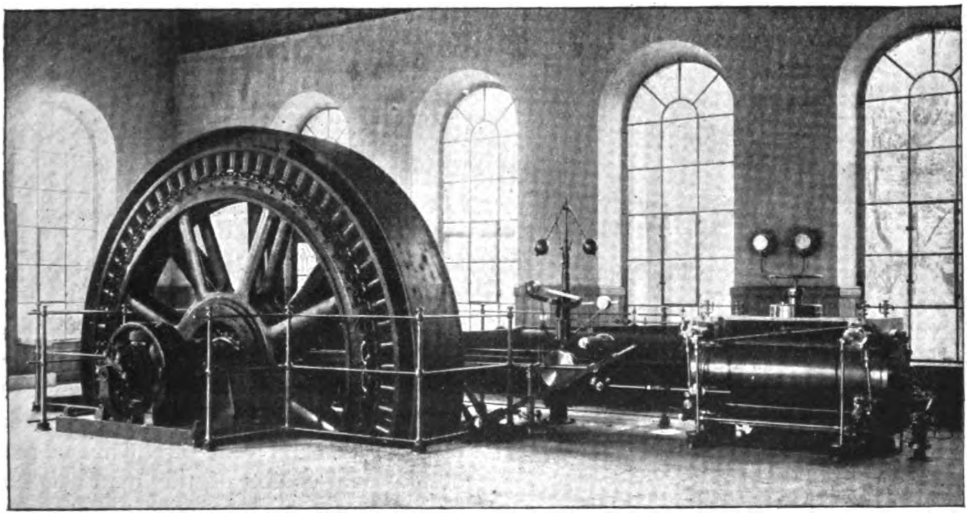


FIG. 494.—COMPLETE MACHINE WITH EXTERNAL REVOLVING FIELD.

very heavy connections are taken out from the armature coils by stout copper passing circumferentially round the machine, the armature coils being connected in parallel in order to meet the heavy current demand. The generator shown delivers 600 horse-power at 375 revolutions and a frequency of 50 cycles. The pressure is only 50 volts. This means an output of 8,960 amperes, which has necessitated so ample a provision of copper in the end connections. The machine is a single-phaser.

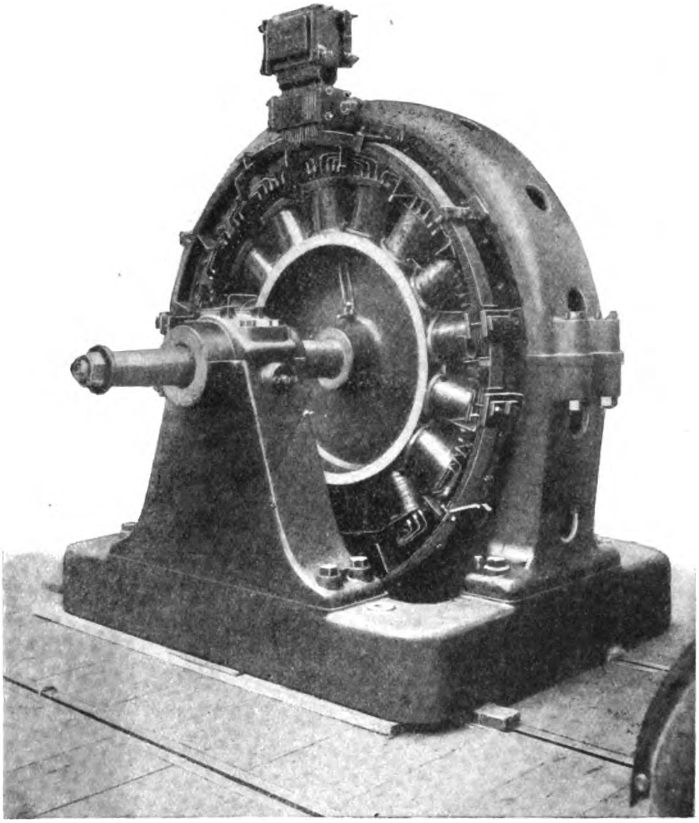


FIG. 495.—BROWN-BOVERI ALTERNATOR FOR FURNACE WORK.

TURBO-ALTERNATORS.

The application of steam turbines to the driving of alternating-current generators has been far more extensive than to continuous-current machines, owing partly to the demand for large alternator units, and partly to difficulties experienced with high speed continuous-current machines.

High speed in an alternator in many ways simplifies the electrical design, and the chief difficulties are mechanical.

With such high speed machinery very great centrifugal forces are brought into play and, also, perfect balance must be secured in the revolving portions, and both of these demand very careful mechanical design and choice of the materials employed.

The design is simplified electrically

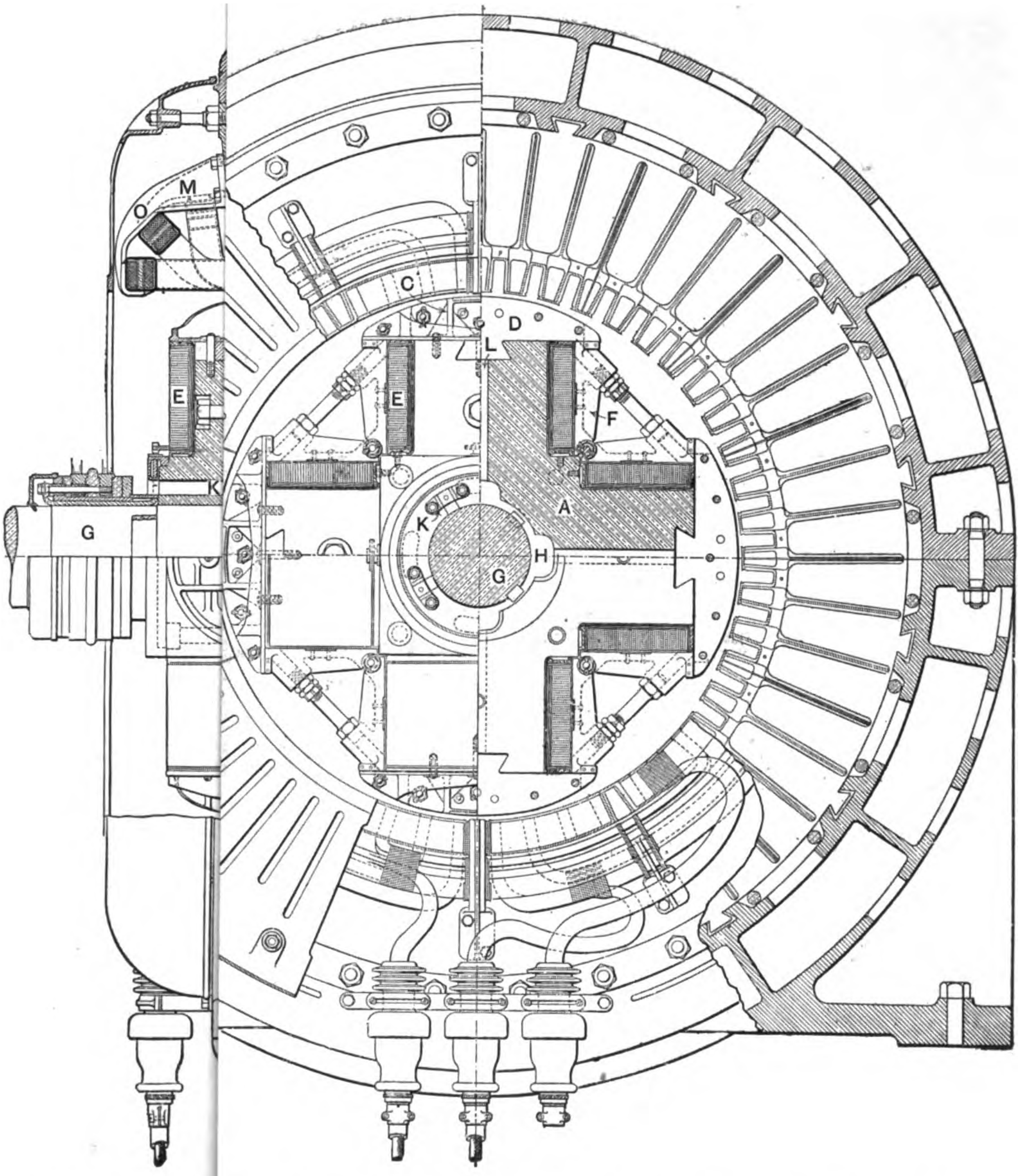


PLATE X.—DETAIL GLASGOW, SHOWING FIELD AND ARMATURE CONSTRUCTIONS. (*See page* 549.)

because of the fact that at these high speeds only a few poles are necessary. Thus 25 ∿ alternators (now commonly used for power transmission) will have only four poles at 750 revolutions per minute, a speed which is not too high for even the very largest turbo units.

Perhaps the chief difficulty in the electrical design is the provision of sufficient ventilation, for, owing to the very high speed of rotation, a small diameter is called for in order to keep the peripheral speed within reasonable limits. This necessarily results in a very long machine, and the conditions become, as regards facility for getting rid of heat, very different from those which obtain in the case of the ordinary flywheel alternator, where the diameter must necessarily be large compared with the axial length, owing to the necessity for making room for a comparatively large number of poles.

Very ample ventilating ducts must be provided through the armature cores of turbo alternators, and in most cases ducts are also carried through the field system.

Another very important point, which has been brought into great prominence by practical experience with this type of machine, is that the armature end windings must be very securely held in place by additional mechanical supports in order that they may not be disturbed by the very considerable electromagnetic forces to which the coils are subjected when the machine is running. This effect in the case of ordinary alternators has given very little trouble, owing to the smallness of the forces at play, but owing to the very large pole pitch resulting in a very large armature coil and the greatly increased magnitude of the forces at work, it has been found inadvisable to rely solely upon the natural rigidity of the end armature projections.

In some cases the magnitude of this effect has been under-estimated, and rather disastrous experiences have resulted.

An interesting point in connection with these large turbo alternators is the long air gap which is necessary in order that the pressure drop shall not exceed a reasonable limit. Reference has been made to the importance of good voltage regulation, and we shall outline at the end of this chapter the considerations affecting the pressure drop in alternators and its calculation; but as the question is a very complicated one, we can only say here that such air gaps are necessary in order that a suitable ratio may exist between the armature and field ampere turns. Air gaps of ¾ in. to 1½ in. are common, and in the case of some units of 5,500 kilowatts recently installed in London the air gap is over 3 in. in length.

EXAMPLES OF TURBO ALTERNATORS.

A 2,500 kilowatt set by Messrs. C. A. Parsons and Co., is shown by a photograph in Fig. 496. Messrs. Parsons were practically the pioneers in steam turbine work, and they have supplied a great many turbo alternator sets. The set illustrated was supplied to the new Carville station of the Newcastle-on-Tyne Electric Supply Company to give a supply at 6,000 volts three phase at 40 cycles. A feature in this machine is the hood, which is slipped over the whole body of the alternator, and which is provided with a kind of chimney at the top, through which the hot air is driven. This ensures that the cooling draught shall effectually traverse the hottest, *i.e.* the central part of the machine.

Full details of a 3,000 kilowatt turbo alternator supplied by Messrs. Dick, Kerr and Co., Limited, to Glasgow are shown by the detail drawing in Plate X., and by the performance curves in Fig. 497. The machine has four poles, and runs at 750 revolutions per minute, the frequency being, therefore, 25 cycles generating

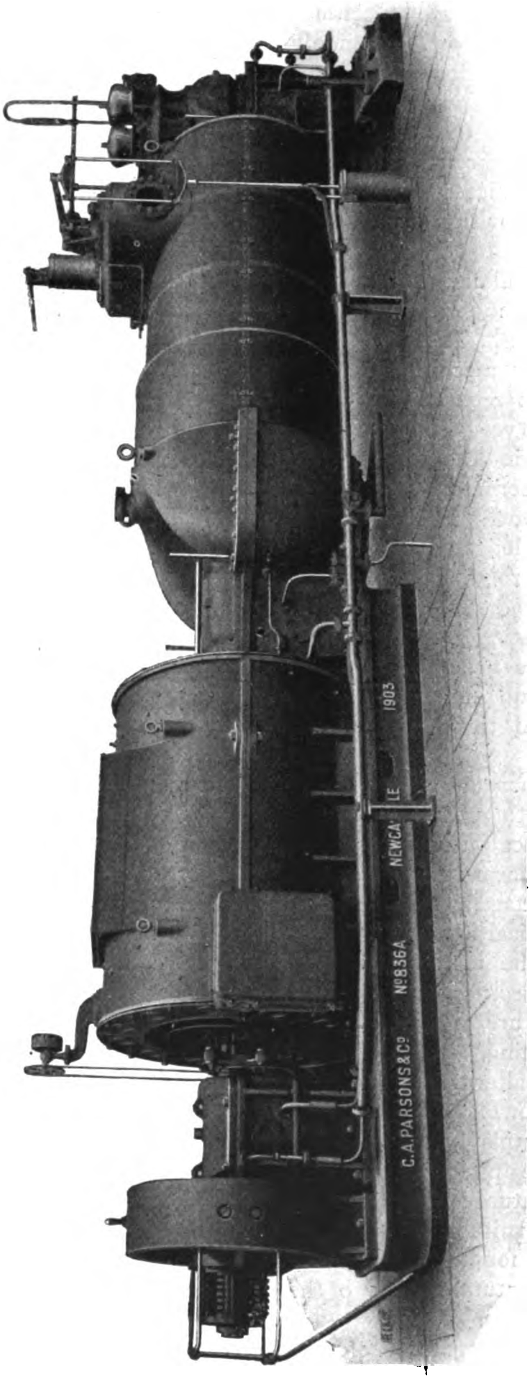


FIG. 496.—PARSONS TURBO ALTERNATOR.

three-phase currents at 6,700 volts across the lines.

The armature frame is a cast-iron box construction, into which the core segments are dovetailed, and ten ventilating ducts, equally spaced, are run through the core to correspond with similar ducts through the field system.

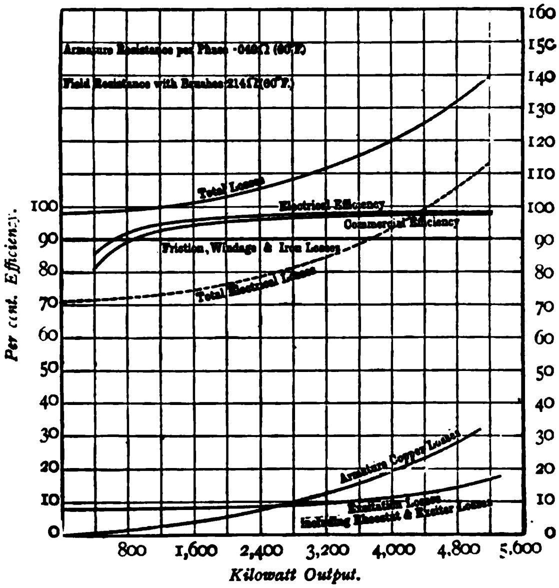


FIG. 497.—DISTRIBUTION OF LOSSES IN GLASGOW TURBO ALTERNATOR BY MESSRS. DICK, KERR AND CO.

The machine can be uncovered for inspection by sliding the stator along the bedplate, the end bearing being first removed to permit the movement to take place. The four-pole revolving field is built up of a central steel casting, A, provided with ventilating holes, L, and laminated pole tips, D, dovetailed on, ample ducts being allowed through the pole tips in order that there may be a circulation of air right through the machine. This is further provided for by the ducts, H and K, in the bore of the steel casting and end plates respectively, by which air, entering axially, flows radially through the ducts, L. The field winding, E, is of edgewound strip, insulated between the turns with paper and mica, and supported in a copper former with heavy insulated flanges. The coils of edge strip, after being formed and insulated, are subjected to hydraulic pressure in the radial direction of almost 50 per cent. above the pressure to which they would be subjected from centrifugal action in normal running.

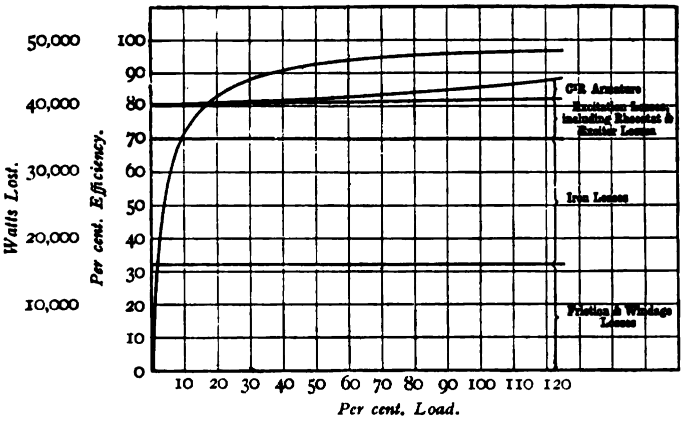


FIG. 498.—PERFORMANCE CURVES OF BRISTOL MACHINE BY MESSRS. DICK, KERR AND CO.

Between the field coils pressure wedges, shown at F, are provided to prevent the tangential component of the various forces resulting from the centrifugal effect from opening the field coils.

Each wedge consists of two limbs hinged together where they meet, and forced against the windings by a screwed strut, as may be seen clearly from the Plate.

A further mechanical feature of importance is the provision for securing the coil ends. Cast brackets, o, with claw-like extremities, are bolted to each side of the stator frame, and engage with the ends of each of the straight coils.

The brackets also house the bent coils, and all three ranges are heavily insulated where they meet the supporting brackets.

The slip rings are of manganese bronze, and are shrunk hot over micanite rings on to a solid steel sleeve.

The performance curves, Fig. 497, show that the efficiency is as high as 90 per cent. at 800 kilowatts, or just over one quarter full load, while at full load it is nearly 97 per cent., a much higher figure than could be obtained from a slow speed alternator of the same output. The excitation losses, including all losses in the exciter and rheostats, are about 10 kilowatts, or ·3 of 1 per cent. at full load, while the armature copper loss comes out at about 12 kilowatts. As the total electrical losses are given as about 83 kilowatts at full load, it follows therefore that the iron losses are 83 — (10 + 12) = 61 kilowatts approximately, or about three times the total copper losses.

An interesting set of curves relating to another of this firm's turbo alternators is given in Fig. 498, where the losses in various parts of a 1,000 kilowatt 1,500 revolutions per minute machine, supplied to the Corporation of Bristol, have been separated from one another and plotted separately, while the resulting efficiency is shown by the highest.

Messrs. Dick, Kerr now adopt a somewhat different construction as regards details from that just described, and one of their latest machines is illustrated in Figs. 499, 500, 501, 502. The laminated pole tips as seen in Fig. 499 are dovetailed into the pole cores, and the end pieces are also dovetailed in and held by bolts, which may be clearly seen in Fig. 499. These bolts run right through the laminations and the end pieces, and the latter serve to hold down the projecting ends of the magnet windings against centrifugal force. The wedges that are placed between the poles are also different from those employed in the machine last described. In the present machine they are formed of open gun metal castings of very stiff design, as may be especially seen in Fig. 499. The wedge comprises

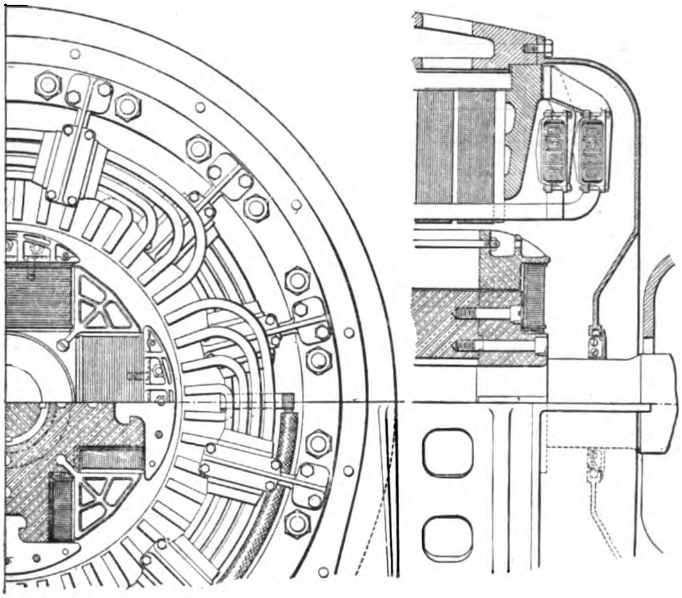


FIG. 499.—DETAILS OF MAGNET WHEEL OF DICK, KERR TURBO ALTERNATOR.

a stalk with an enlarged end which is forced into a groove in the steel pole, forming a kind of dovetail which makes the fixing of these wedges very secure. The field winding is copper strip wound on edge, the insulation between the turns consisting of strip paper and mica. The projecting ends are varnished over with a special varnish proof against oil and water. After having been wound and insulated these coils are compressed as in the previous case with a pressure roughly 50 per cent. in excess of the centrifugal pressure to which they will be subjected when running.

The slip rings making connection for the exciting current are of cast iron of a carefully selected brand, shrunk on to a sleeve over micanite rings. The sleeve is of solid steel and is forced on to the rotor shaft. Connection between the rings and the field windings is provided by extremely flexible thin copper strip, and this, when in position, is protected by a cap, which can, however, be easily removed for inspection. The rotor body is cast steel, cast under pressure; it is mounted by being machined and bored out to a diameter larger than the outside diameter of the shaft, and is subsequently mounted on cross pieces, which are keyed to the shaft. The cross pieces contain circular grooves, with which circular projections machined on the magnet body engage. These key

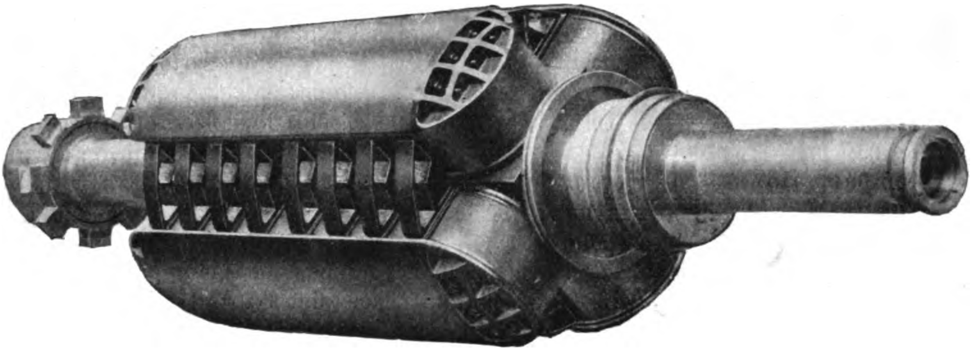


FIG. 500.—MAGNET WHEEL OF DICK, KERR TURBO ALTERNATOR.

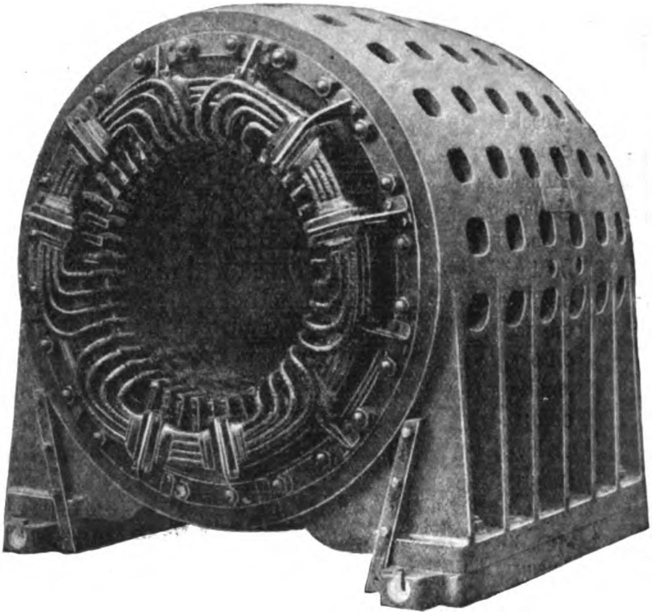


FIG. 501.—ARMATURE OF DICK, KERR TURBO ALTERNATOR.

the parts together against centrifugal forces, and screws passing from the end cross pieces into the magnet body secure them against axial displacement. Exceptionally rigid cramps are provided to hold the end windings of the armature, each cramp being made in two pieces, which are bolted together, as is shown especially in the right hand portion of Fig. 499. The complete machine is illustrated in Fig. 502, and gives an output of 2,000 kilowatts at 5,200 volts, and a power factor of 0·85, the frequency being 50. An overload of 20 per cent. for two and a-half hours continuously may be taken without overheating. Ventilation is slightly improved by partially closing the end shield. This would appear at first sight to be prejudicial rather than advantageous, but, as a matter of fact, while the volume of air is not much decreased, owing to increased velocity, the path of the air is better controlled, it being constrained to enter at the centre, and thus traverse every part of the machine properly.

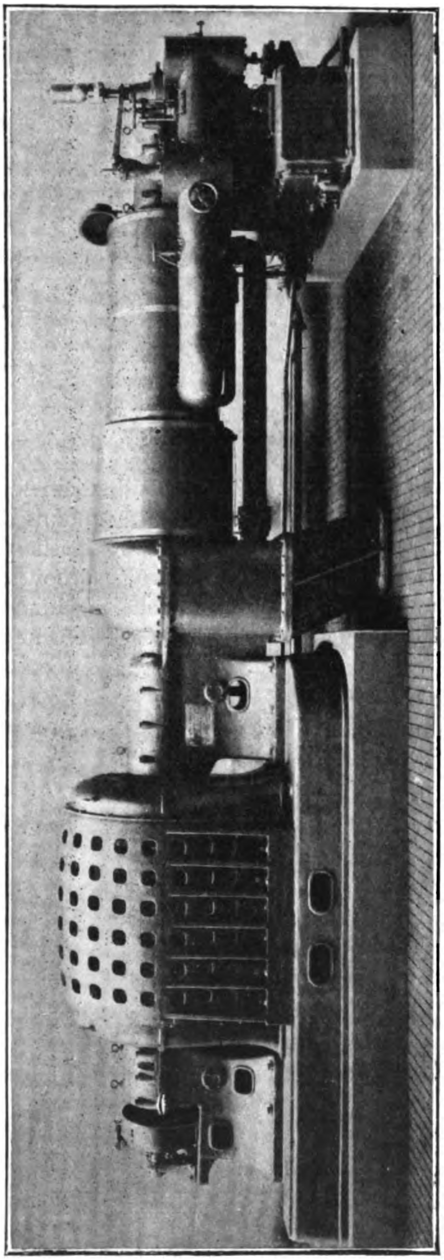


FIG. 502.—WILLANS-DICK, KERR TURBO ALTERNATOR COMPLETE.

TRANSFORMERS.

As examples of the specific constructions, the types of transformer manufactured by Messrs. Johnson and Phillips, the British Electric Transformer Company, and Messrs. Brown, Boveri and Co. have been selected.

JOHNSON AND PHILLIPS.

This transformer is of the core type and is fully illustrated in various forms in Figs. 503 to 506. In Fig. 503 parts of transformers in various stages of construction are to be seen, and it will be noticed that there are two three-phase transformers prominent in the illustration. An examination of these two cores shows that the three limbs of the lower yoke are formed of E-shaped stampings, and that there are thus no magnetic joints, that is to say, no joints across which magnetism has to pass in this portion of the core, so that the path of the flux may be entirely in iron. The upper yoke, however, is made separately, and makes a butt joint with the carefully faced ends of the

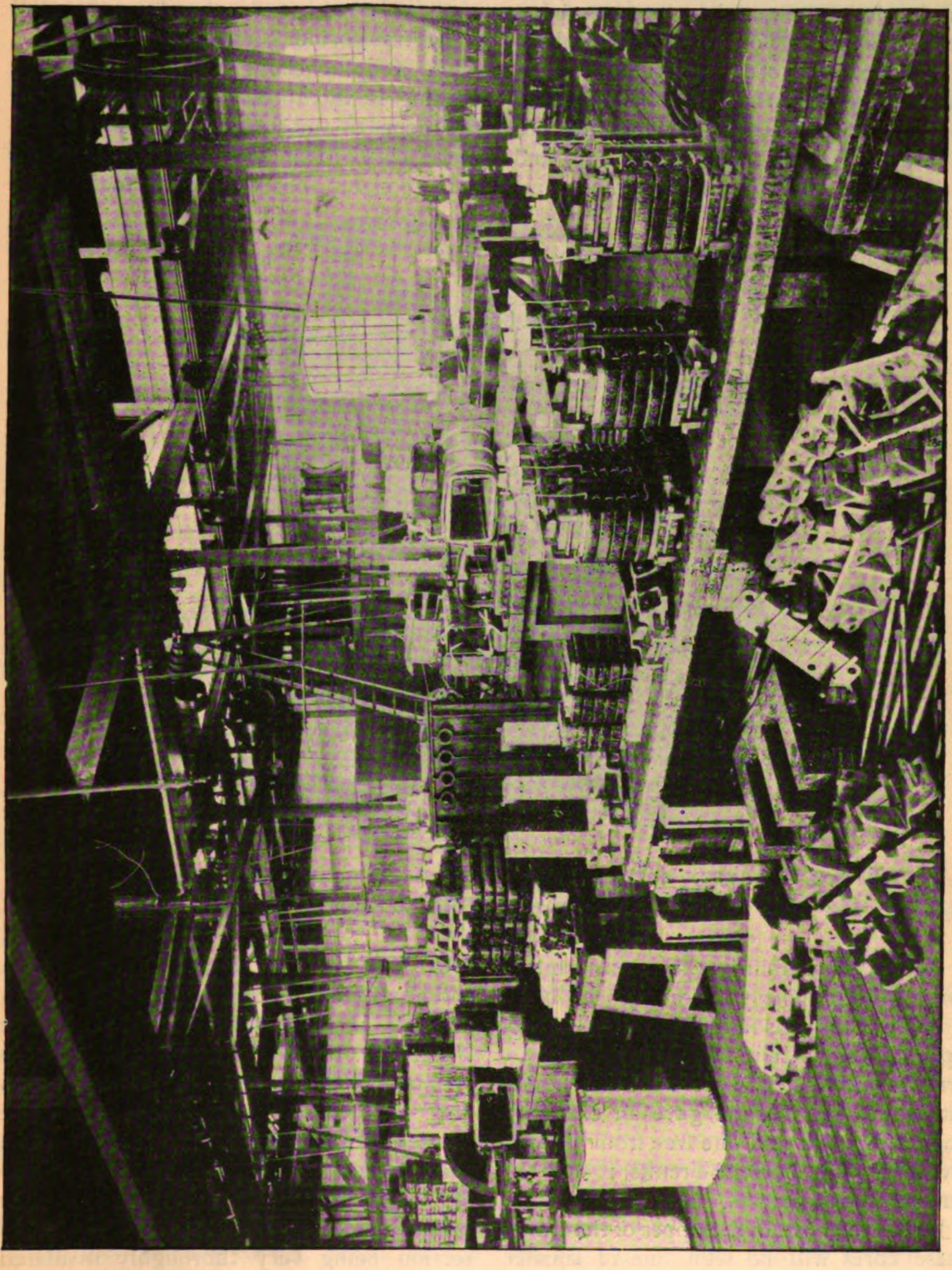


FIG. 503.—CORE TRANSFORMERS IN VARIOUS STAGES OF COMPLETION IN THE WORKS OF MESSRS. JOHNSON AND PHILLIPS, LIMITED.

three limbs and its own edge surface, which is also carefully fitted. A sheet of very thin insulating material is interposed between this upper yoke and each limb to prevent circulation of eddy currents between adjacent laminations. The object of this mode of construction is to enable the coils to be wound ready to be slipped on, and to avoid the cost of an imbricated joint in finally asssembling the transformers. Formerly the upper yoke had to be built in over the coils after they had been slipped into position in such a way as to form an imbricated joint with the limbs, but while this method gave an excellent magnetic circuit and one free from air gap and from eddy current circuits, it was expensive in labour.

Just to the right of the upper of the three-phase cores will be seen one of smaller dimensions with the coils already slipped into position, and again, to the right of that, a cast iron framing which holds the upper yoke ready to be placed upon the top of the transformer complete with its coils. Such a yoke clamped in its cast-iron framing is also to be seen upside down on the floor to the left of the lower three-phase core. The cast-iron framings serve both to clamp the laminations together in a direction at right angles to their plane and also by means of lugs to provide holding for bolts running parallel with the limbs ; by these bolts the top yoke is clamped securely down on the limbs and the whole held rigidly together. These clamping bolts are best seen in the three completed transformers to the right hand of the picture. The primary coils are wound in sections, each section being very thoroughly insulated by hand, dried in vacuum, and then impreg-

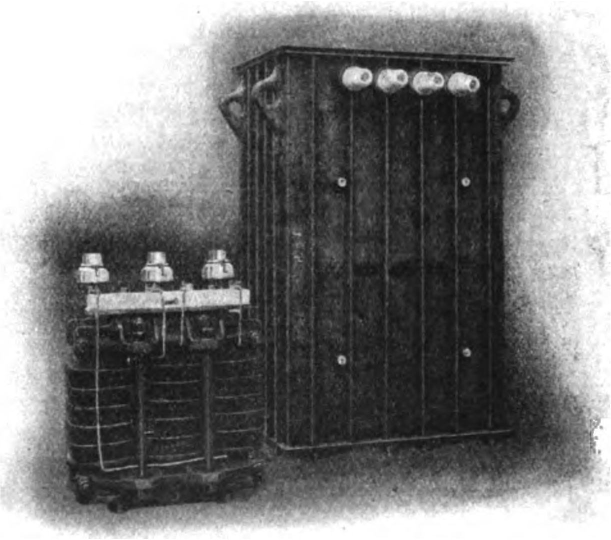


FIG. 504.—JOHNSON AND PHILLIPS' THREE-PHASE CORE TRANSFORMER AND CAST-IRON CASE, OIL COOLED.

nated with varnish. The secondary coils are wound of bare copper, neighbouring turns being insulated from one another by a very thin sheet fibre or presspahn slipped in between the turns, and the whole thoroughly varnished and baked. When thus treated it forms an extraordinarily solid construction, each coil looking like a rectangular tube; it may be freely handled without the turns coming apart, and when struck with the knuckles or a mallet, gives a resonant response indicative of great rigidity. The primary coils are clearly seen in position in the completed transformers in the front of the illustration, whilst one or two secondaries made in the manner described, are to be seen stacked upon the benches in the centre of the background

The larger transformers are placed in cast iron cases which are subsequently filled with oil, the exterior of the cases being provided with ribs to facilitate radiation of heat. Riveted cases of wrought iron are also used, and examples of both types are to be seen in Fig. 503. The terminal insulation throughout is porcelain, the ends of the primary winding being brought up to porcelain insulators mounted on iron stalks attached to the top yoke clamp, and the outgoing wires brought in through porcelain bushes placed in holes in the case, as seen in Fig. 504.

Transformers for much larger outputs and for higher voltages are sometimes mounted in an open framework as shown in Fig. 505. The massive copper connections of the secondary winding of this

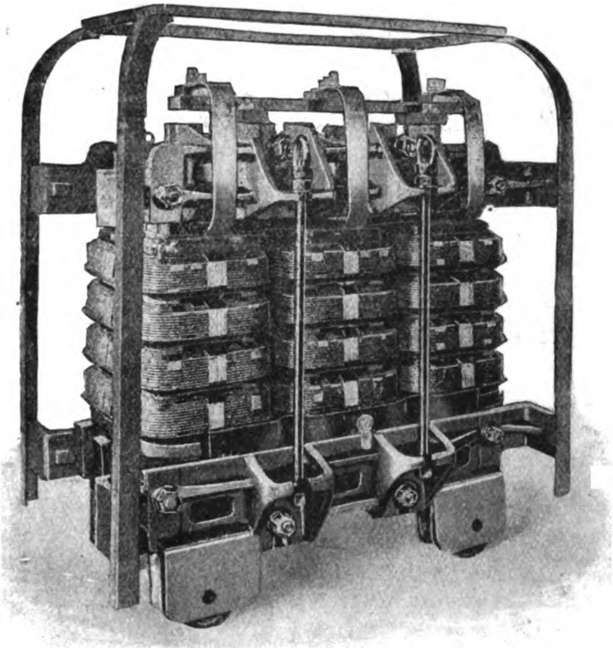


FIG. 505.—JOHNSON AND PHILLIPS' AIR-COOLED TRANSFORMER AND CASING FRAMEWORK.

transformer are very clearly seen. In any of these constructions the whole transformer can be dismantled by merely releasing four nuts, thus allowing a burnt-out coil to be replaced or other repair effected with a minimum expenditure of both labour and time. The reassembling merely involves replacing the nuts and tightening them up until the top yoke is properly clamped in position. In some cases an oil break switch and fuses are attached to the exterior of the case as shown in Figs. 506 and 507. The fuse boxes and switch with the porcelain insulators of the latter and its operating link are clearly seen in Fig. 506, while the connection of the switch is to be understood from a reference to Fig. 507, where it is seen both with and without the oil tank.

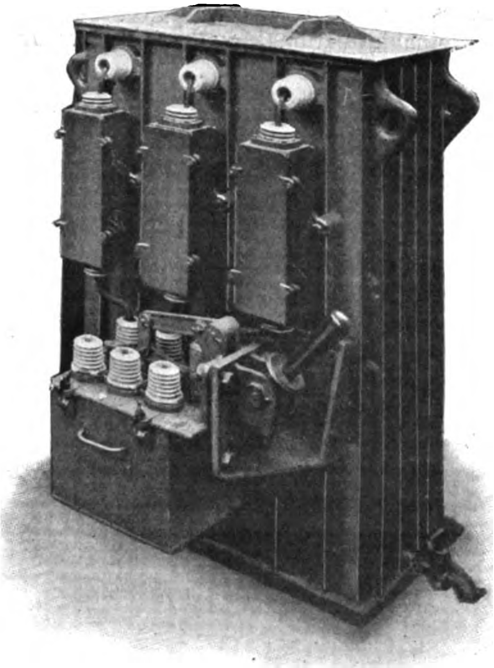


FIG. 506.—ARRANGEMENT OF OIL SWITCH AND FUSES ON JOHNSON AND PHILLIPS' THREE-PHASE TRANSFORMER CASE.

BERRY TRANSFORMER.

The Berry transformer exhibits a unique construction, the core being built up of a number of groups of **L**-shaped laminations arranged together so as to form a hollow cylinder, the long limbs of the **L** forming the wall of the cylinder, and the short limbs projecting outwardly to form an external flange. In point of fact each lamination is not **L**-shaped, but the **L** is made of two straight pieces joined together at the angle. In the course of manufacture these are brought into position by being built up round a mandril and held in place by wooden wedges and binding wire. The coils are wound on the outside of the cylinder. The various stages of manufacture are illustrated in Figs. 508 to 515, which are reproductions from photographs kindly supplied by the British Electric Transformer Company. When the laminations have been assembled so as to form the central cylindrical core, this is insulated and mounted in a winding machine (Fig. 508) and a secondary winding is wound immediately over that (Fig. 509). In the

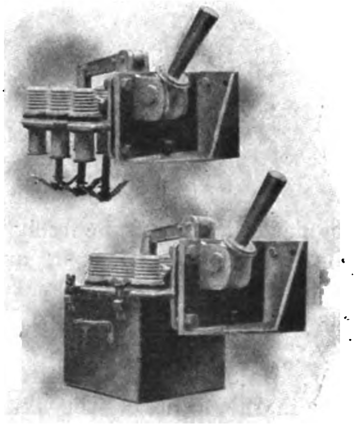


FIG. 507.—DETAILS OF OIL SWITCH FOR JOHNSON AND PHILLIPS TRANSFORMERS.

example shown the secondary winding consists of several flat copper tapes put in parallel, which are insulated by hand with cotton tape as the winding proceeds. In this case, the end to be connected to a terminal is seen at the right hand of the core, held in position by clamps and a band of hoop-iron during the process of winding. When this first layer has been completed the left hand end is brought out and clamped, as seen in Fig. 510. The primary winding is prepared in sections by winding coils upon a wooden former or dummy, four completed sections, and a fifth in position on the dummy, being seen in Fig. 511. These are wound of insulated wire, and the sections are hand insulated throughout. They are then slipped over the inner secondary, which is shown in Fig. 510, and the appearance of the transformer is then as Fig. 512. A layer of insulation is then put over the primary, and a second secondary winding, similar to the first and distinguished from it by being called the outer secondary (the other is called

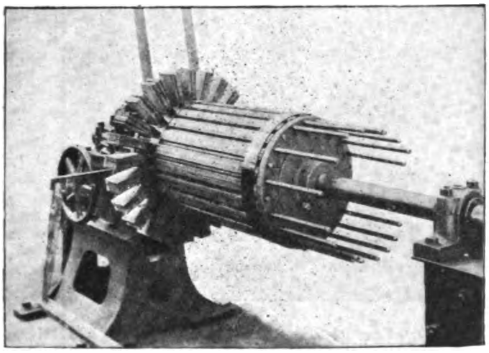


FIG. 508.—CENTRAL CORE OF BERRY TRANSFORMER.

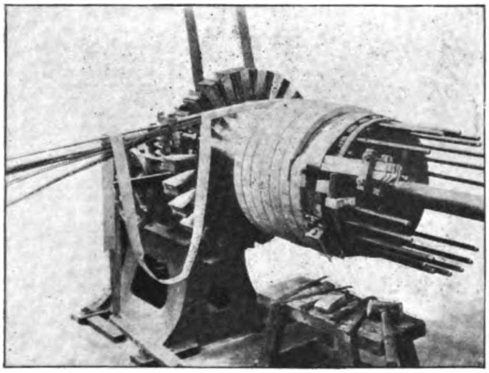


FIG. 509.—INNER SECONDARY BEING WOUND.

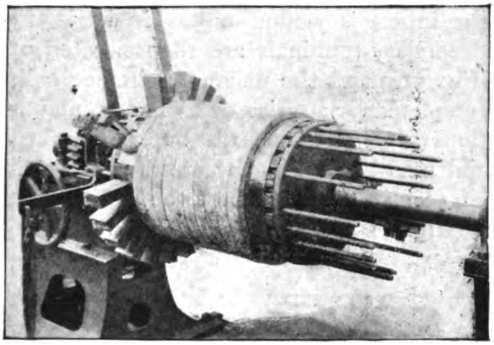


FIG. 510.—INNER SECONDARY COMPLETED.

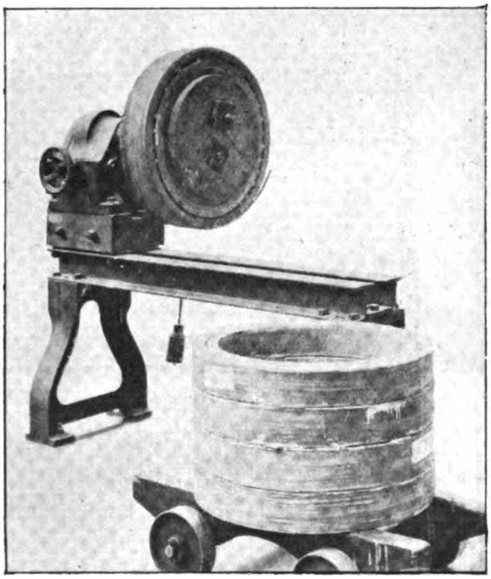


FIG. 511.—PRIMARY SECTIONS FOR BERRY TRANSFORMERS.

the inner) is wound on as in Fig. 513. Secondary terminals are then sweated on (Fig. 514) and the magnetic circuit finally completed by a series of L-shaped laminations placed outside the outer secondary and held in position by bolts, whose ends are seen in Fig. 514, and a top casting seen in Fig. 515. The windings in the completed transformer are thus encased between two concentric cylinders of laminations. Owing to the greater diameter of the outer cylinder as compared with the inner, the magnetic circuit at this part can be made as good as that of the inner cylinder without

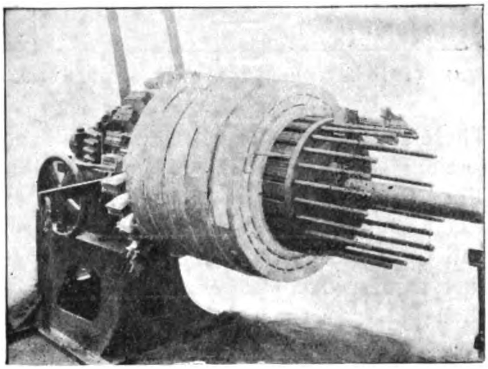


FIG. 512.—PRIMARY SECTIONS IN POSITION OVER INNER SECONDARY.

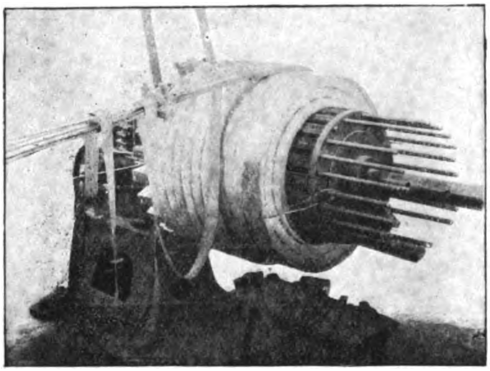


FIG. 513.—OUTER SECONDARY IN PROCESS OF WINDING.

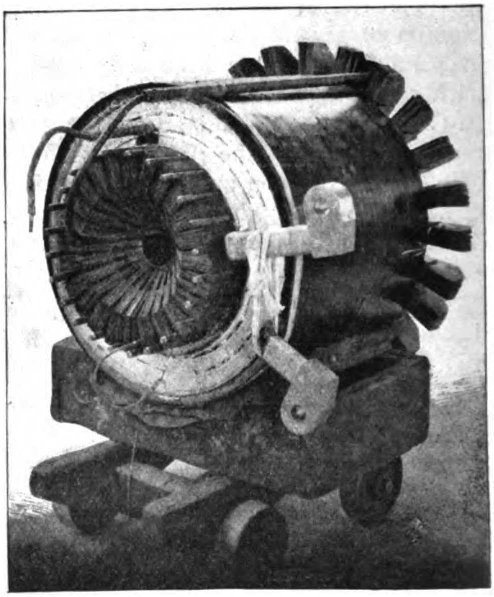


FIG. 514.—INNER CORE AND WINDINGS COMPLETE; OUTER LAMINATIONS NOT YET IN PLACE.

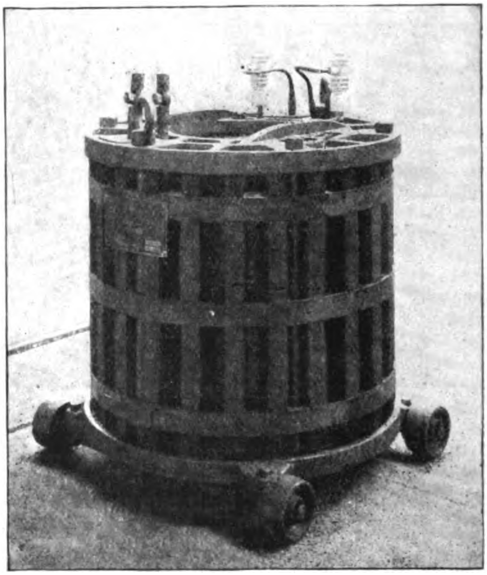


FIG. 515.—COMPLETE BERRY TRANSFORMER, SHOWING VENTILATING GAPS IN OUTER LAMINATIONS.

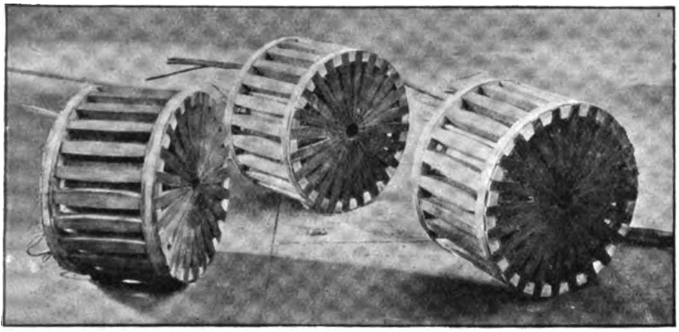


FIG. 516.—THREE SINGLE-PHASE BERRY UNITS FOR THREE-PHASE WORK.

occupying the whole periphery. The outer cylinder, therefore, is not complete, but has, parallel to its axis, long openings which provide for free ventilation. Strictly speaking this transformer is a shell transformer, for the windings are entirely enclosed in iron. So far as manufacture, however, is concerned, it is almost equivalent to a core transformer for ease in winding and assembling. For three-phase work the process of manufacture is identical, and three single-phase limbs are assembled to form a three-phase transformer (Fig. 516) instead of providing a three-core design similar to those described above as made by Messrs. Johnson and Phillips. The method of construction here described is employed by the British Electric Transformer Company for sizes up to 2,000 horse-power. No artificial method of cooling is used, except for very large sizes, when an air blast is applied. The construction affords an excellent protection to the windings and makes the completed transformer very compact and easily handled without fear of damage. A sectional drawing of a complete transformer is given in Figs. 516 (*a*) and (*b*).

BROWN - BOVERI TRANSFORMERS.

A transformer of very large output is illustrated in Fig. 517. This transformer is intended to deliver an output of 350 kilo-volt-amperes. It is a single-phase transformer of the yoke type, a noteworthy feature being the very massive secondary windings. The duty of the transformer is

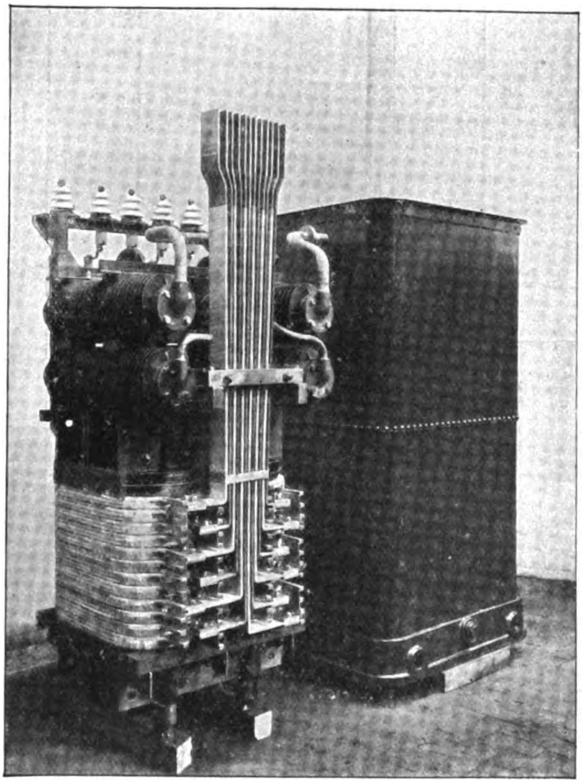


FIG. 517.—BROWN-BOVERI TRANSFORMER, OIL COOLED, WITH WATER CIRCULATION; 7,000 AMPERES SECONDARY CURRENT.

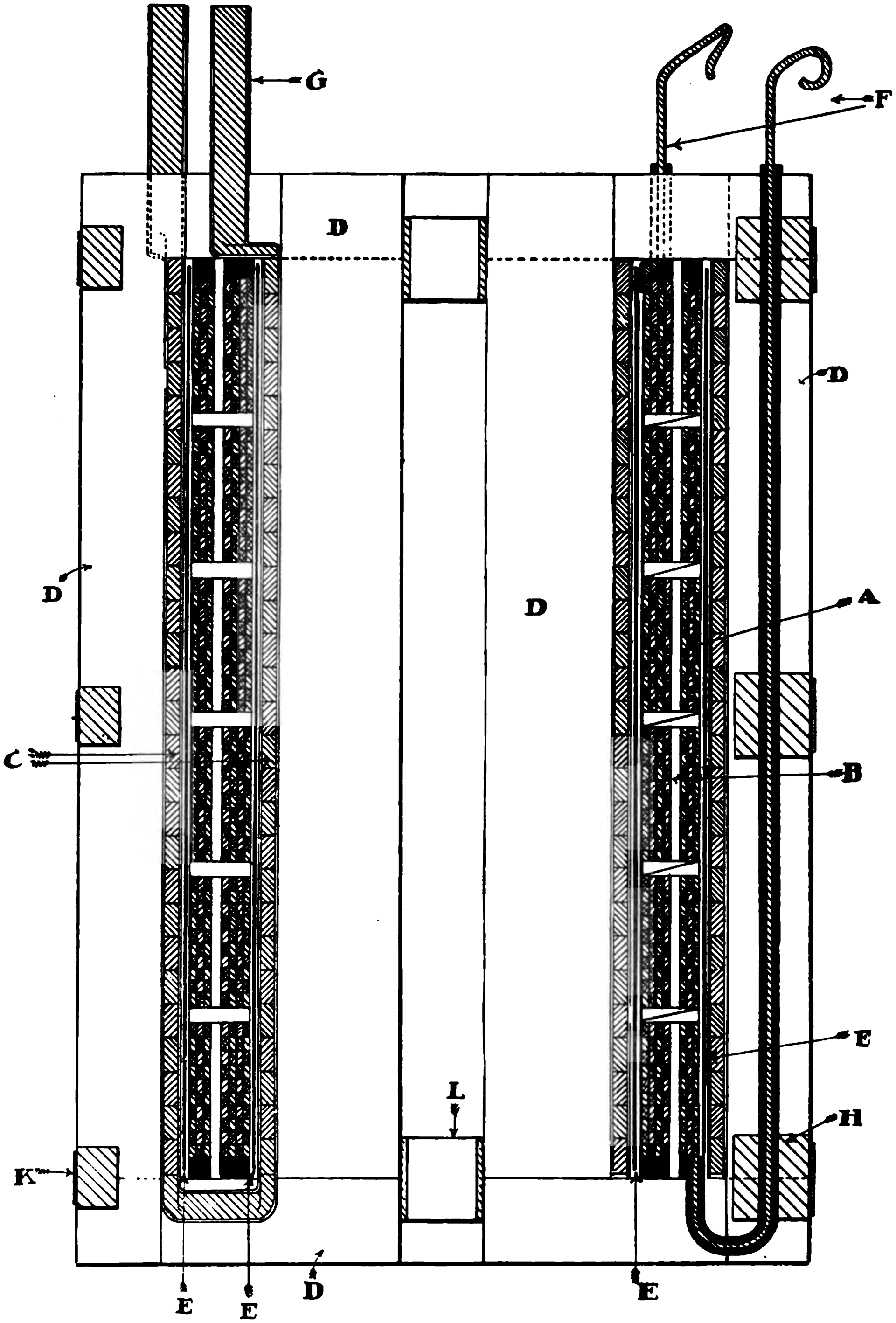


FIG. 516*a*.—SECTIONAL ELEVATION OF COMPLETED THREE-PHASE TRANSFORMER.
(*For references see opposite page.*)

A	PRIMARY COILS FORMER WOUND IN SECTIONS
B	AIR SPACES IN SAME
C	SECONDARY COILS WOUND ON CORE
D	IRON CIRCUIT
E	EARTH SHIELD
F	PRIMARY INSULATED LEADS
G	SECONDARY CONNECTIONS
H	WOOD SPACING BLOCKS
K	STEEL BANDS
L	CORE RINGS

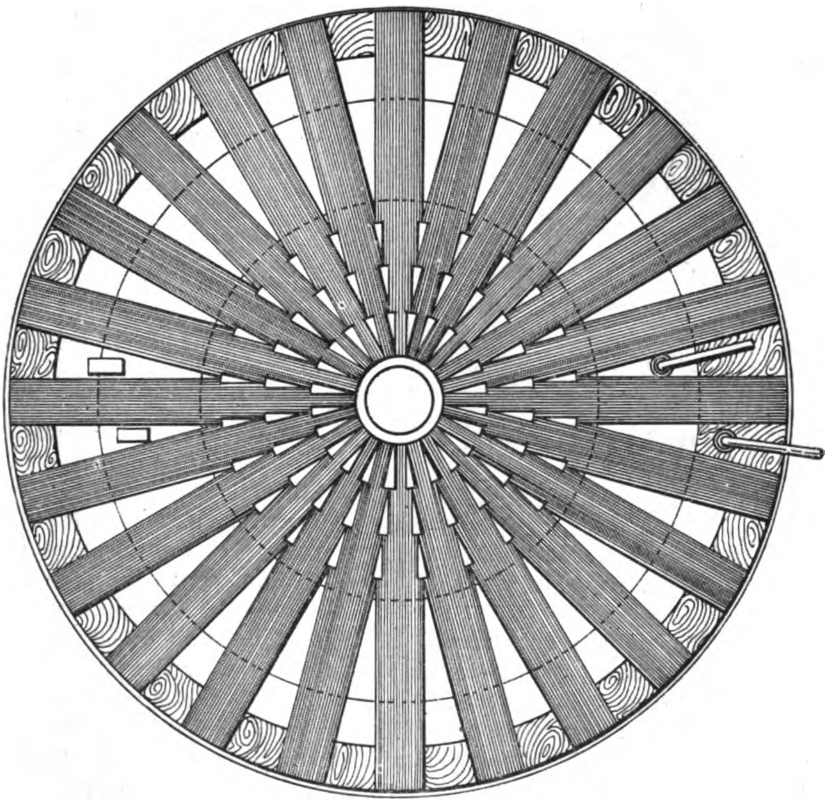


FIG. 516*b*.—PLAN OF A COMPLETED THREE-PHASE TRANSFORMER.

to supply current for the manufacture of calcium carbide at a pressure of about 50 volts, which means a current output of 7,000 amperes. The transformer is oil immersed, the tank being seen to the right of the transformer in the illustration. The cooling of the oil is effected by water circulation through a series of closed chambers seen immediately over the transformer, and the chambers are provided with numerous very deep external flanges to facilitate as much as possible the passage of heat from the oil to the circulating water inside the chambers.

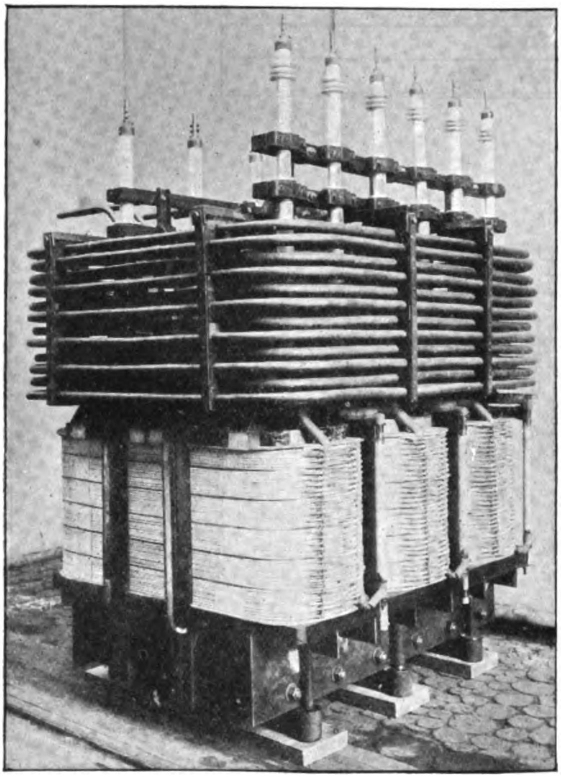


FIG. 518.—BROWN-BOVERI THREE-PHASE TRANSFORMER; 24,300 TO 5,000 VOLTS.

In Fig. 518 is illustrated another transformer by the same makers for an output of 2,500 kilowatts at 50 cycles on a three-phase circuit. It is like the last one, of the core type and oil immersed. It differs from it, however, in being a three-core three-phase apparatus and for 24,300 volts on the high-tension side, transforming down to 5,000 volts. The coils are wound in sections, taped together, and slipped on, and the end connections are very substantially protected in porcelain tubes, three of which can be seen carrying the connection from the bottom end of each of the limbs. The terminals are all carried on long porcelain tubes, those on the high-tension side being also provided with three flanges to reduce leakage. The porcelain tubes are firmly clamped to supports and surmount the cooling device, which is placed between them and the top of the transformer yoke. The cooling device consists of a large rectangular frame built of piping, to constitute a water circulating coil.

A device which is essentially a transformer is the induction regulator, a perfected form of which has recently been introduced by Messrs. Brown, Boveri and Co. This apparatus in external form and all the main features of construction is almost identical with an induction motor. In operation, however, it differs from one, in that the central portion, which corresponds to the rotor, does not revolve, but merely moves through a small angle of about 90°. This movement is effected for the purpose of regulation, the whole device being really a transformer whose mutual induction between the primary and secondary circuits is variable. In principle this is not new, but the present method of carrying out the idea appears to be novel. The device can be arranged for single or polyphase cir-

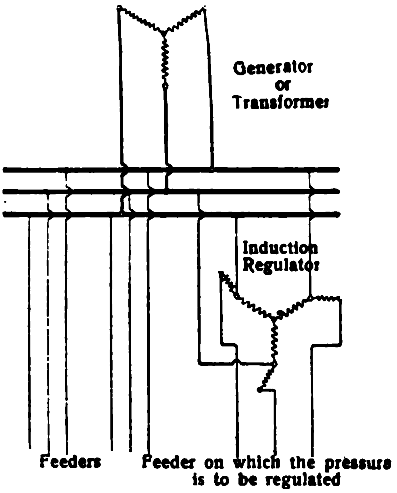


FIG. 519.—CONNECTIONS OF BROWN-BOVERI INDUCTION REGULATOR FOR FEEDER REGULATION.

cuits, and may be hand operated, or automatically operated by means of a relay and subsidiary motor. The stator is usually wound like a four-pole induction motor stator, and the secondary winding on the rotor provides an additional voltage which may be arranged so as to assist or oppose, and in a greater or less degree according to its position, the varying voltage which it is required to regulate. In this way it is serviceable for regulating the pressure of feeders at the outgoing point, and may be adjusted either to vary the supply pressure in proportion to the load, or to maintain constant the pressure at the feeding point independently of station pressure variations. Minor uses may also be found for it: to provide a balancing load for an unequally loaded polyphase system, or again for inserting an opposing E.M.F. in the circuit of high pressure underground cables of considerable length at the moment of switching them in. This opposing E.M.F. is then gradually reduced until the full pressure is applied to the cables. The great feature of the device is that it permits the extra voltage, whether assisting or opposing, to be varied continuously, that is, without jumps, from nothing up to the full value. The automatic regulation is, of course, generally to be preferred, but involves the use of an automatic regulator relay and motor, a Thury type being usually employed. The connections of the circuits for the various purposes outlined above are shown in Figs. 519 to 521, and a regulator for hand

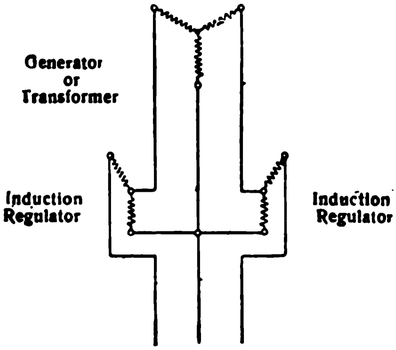


FIG. 520.—CONNECTIONS FOR INDUCTION REGULATORS BALANCING UNEQUALLY LOADED POLYPHASE SYSTEM.

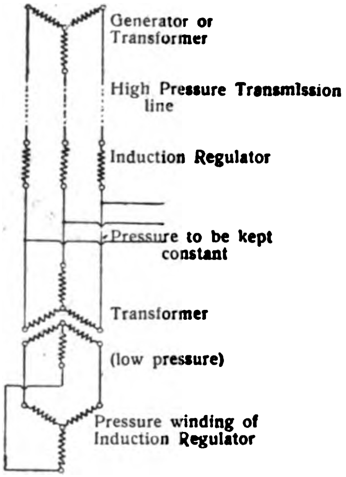


FIG. 521. — CONNECTIONS OF INDUCTION REGULATOR WITH WINDINGS SUPPLIED THROUGH STEP-DOWN TRANSFORMER.

operation showing the segmental rack is given in Fig. 522, while an automatically controlled regulator is shown in Fig. 523.

WELDING TRANSFORMERS.

Transformers find an interesting application for welding purposes where welds have to be carried out between either curved or straight bars, and the method is one of great simplicity and rapidity. Ordinary hand welding is always expensive, and is frequently very difficult, while the reliability of a weld, unless a highly skilled smith be employed, is always open to question. The goodness of a weld depends almost entirely upon the careful adjustment of the temperature, upon the use of a suitable flux, and above all upon the thorough removal of the flux between the surfaces to be joined, either by hammering or otherwise forcing them into the most intimate contact at every point. If, however the two ends of metal to be joined are brought into contact with one another, and an enormously heavy current (relatively to the ordinary carrying capacity of the section) is passed between them, they may be rapidly raised to a welding temperature, and if endwise pressure is then applied the plastic metal will flow. This ensures perfection of contact, which may be further secured by hammering, and the current is then turned off and the joint allowed to cool. The method affords great ease in adjustment of temperature, and as the metal is never exposed actually to the

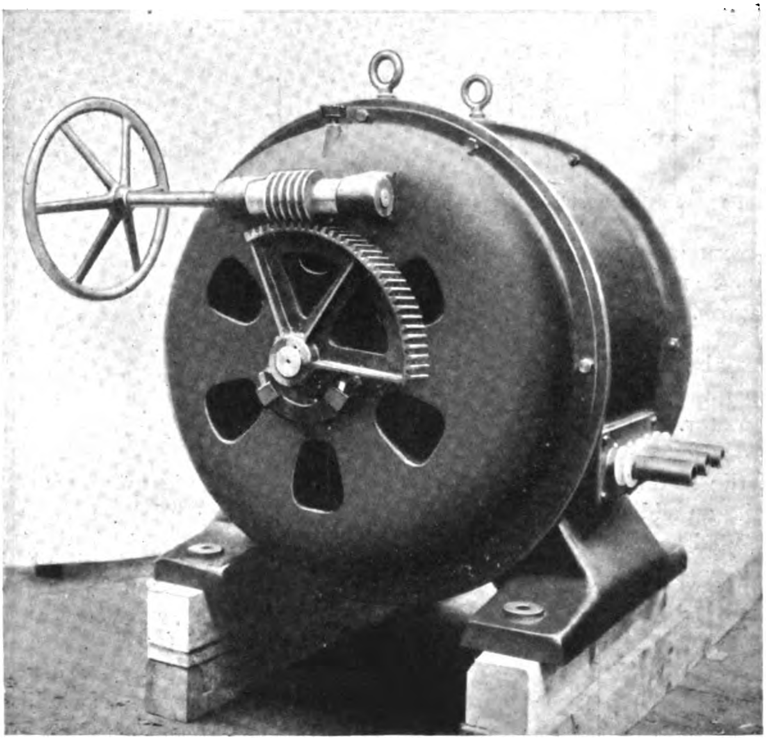


FIG. 522.—HAND-ADJUSTED INDUCTION REGULATOR BY BROWN-BOVERI AND CO.

flames of a fire the entrance of sulphur and other impurities is avoided and the surface may be perfectly protected by a borax or other flux. Transformers for making heavy welds in tram rails are not infrequently employed, especially in America, and smaller transformers are very commonly used in wire-drawing works for uniting the ends of wire to form a long length of cable. With them from sixty to a hundred welds per transformer can be made in an hour by unskilled labour in wire up to three-eighths of an inch diameter, the number of welds depending on the size of the wire. The complete apparatus consists of a transformer and two clamping devices intended to receive the ends to be welded. One of these is movable and is attached to a lever by which pressure may be brought to bear upon the joint when the ends are heated; this occasions an intimate contact and effects the extrusion of the plastic metal, so ensuring elimination of all the flux. An excellent device of this kind is made by the British Insulated and Helsby Cables, Limited, one of the machines being illustrated in Fig. 524, and the circuit shown in Fig. 525. The transformer is

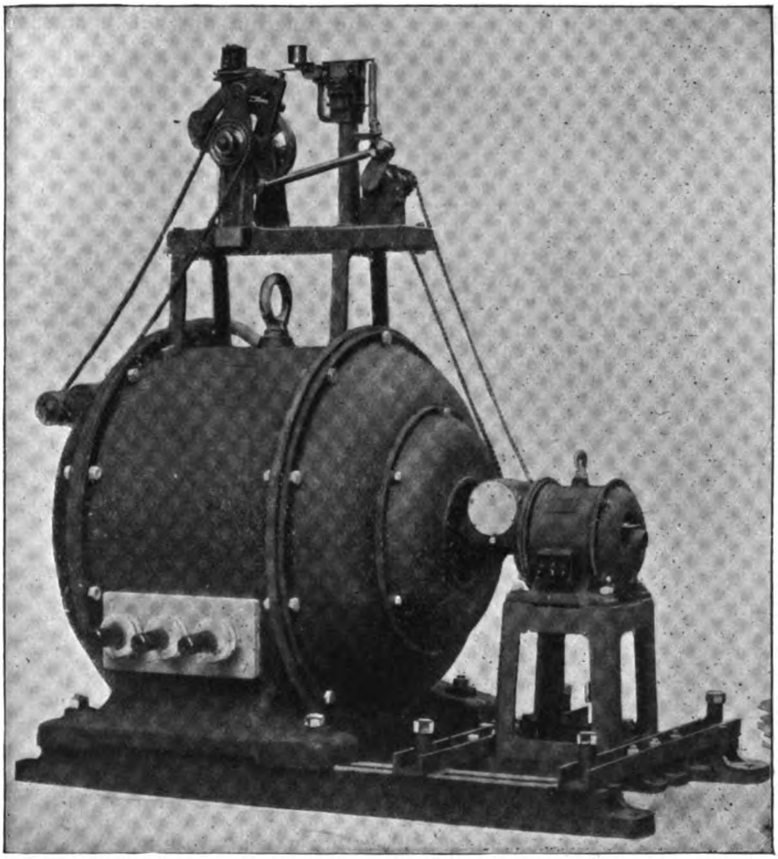


FIG. 523.—BROWN-BOVERI AUTOMATICALLY CONTROLLED REGULATOR.

made with a single-turn secondary, marked S S in Fig. 525, this secondary also constituting the main casting of the welder, so as to enclose and protect the primary. The clamps, C C, are mounted direct upon the ends of the secondary, the fixed one being seen to the left, and the movable one with its sliding bed to the right in the diagram. Two pieces of metal, B B, are shown in position. For very large work a water-cooling arrangement is supplied so as to prevent the clamps becoming overheated by conduction from the intense heat generated at the weld. A weld of the metal and one bent after welding to show the strength of the weld are given at A and B respectively in Fig. 526. A device of this kind saves both its cost and the current consumption many times over in a cable works where several hundred welds have to be made daily.

There is a further type of transformer which, although its application is very limited, possesses considerable interest. It is known as a "constant current" type. The function of the apparatus is, as its name implies, to deliver a secondary load of a current which is virtually constant at a variable pressure. These conditions are the converse of those under which ordinary lighting and power transformers have to operate. In the latter, as has been already pointed out, the secondary voltage, which it is desired to keep as constant as possible, suffers variation owing, in part, to magnetic leakage. This fact is taken advantage of

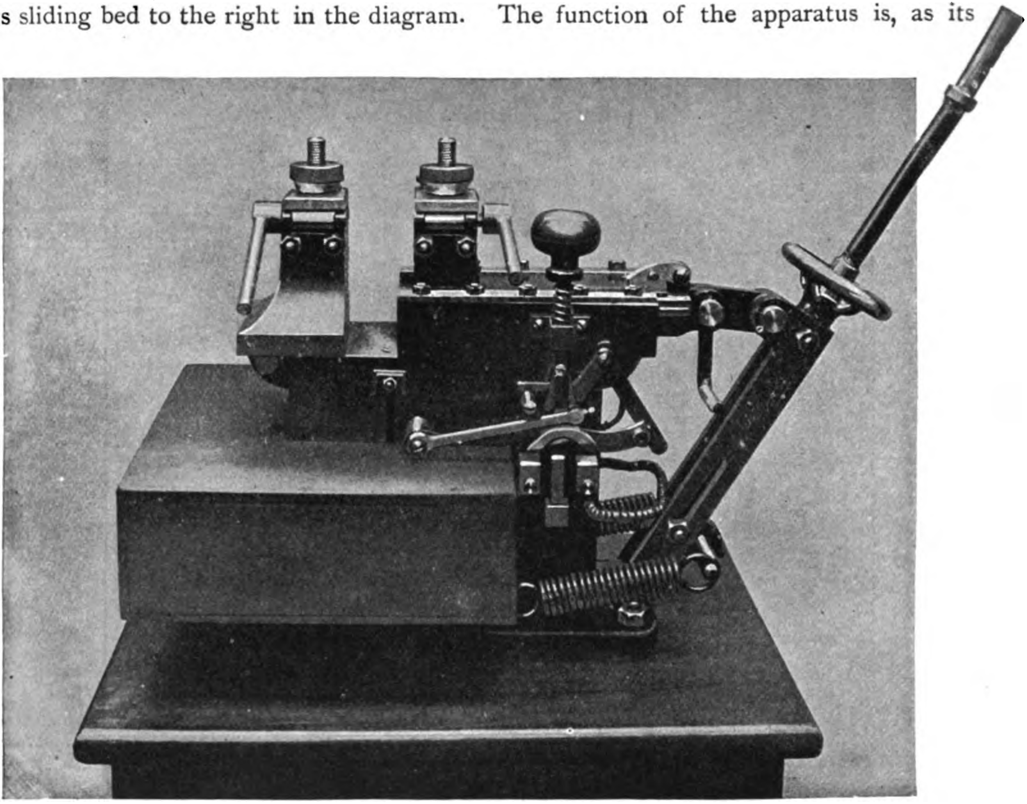


FIG. 524.—WELDER FOR CABLE-MAKING WORKS.

in the constant current type, in order to produce large variations of voltage. The desired variation being large, it follows that at low (secondary) voltage a large leakage is desired, while at full voltage, far less, or indeed as little as possible, is wanted. This leads to the need of a varying magnetic leakage, which is provided for by making the secondary coil loose upon the core and movable. The core is like that of a three-core three-phase transformer, but the middle core only is wound. The primary is wound on a bobbin next to the core and over this is the secondary. The secondary is wound in two halves, the two being brought together by a flexible connection and having flexible connections to their outer ends. The repulsive actions between these two coils tend to force them apart with a force depending upon the current flowing. The coils are supported by a scissors lever and partly counterpoised. If the current exceeds the desired value, the coils part under the repelling force of the currents flowing in them, and when parted the magnetic leakage increases and the voltage at the terminals decreases, so allowing the current to fall off, and restoring it to the desired value. The secondary coils thus are continually moving, so long as there is a variation in the resistance of the circuit supplied, and they have a definite position corresponding to each value of the terminal voltage.

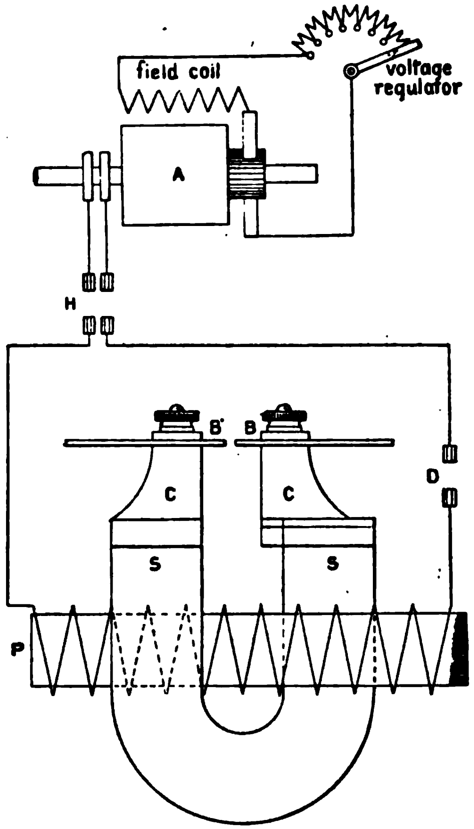


FIG. 525.—CIRCUITS OF HAND WELDING TRANSFORMER.

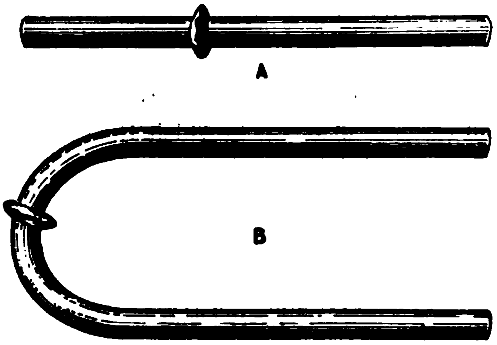


FIG. 526.—BRASS WELD SHOWN AT A; BENT AT B TO SHOW STRENGTH OF WELD.

CHAPTER VI.—INDUCTION MOTORS.

THE FIELD—THE ROTOR—ELEMENTARY NUMERICAL RELATIONS—HEYLAND DIAGRAM—PREDETERMINATION OF THE "DISPERSION COEFFICIENT" OF A GIVEN MOTOR—MECHANICAL CONSTRUCTION OF INDUCTION MOTOR: DESIGN OF INDUCTION MOTOR—EXAMPLES OF INDUCTION MOTORS—SPEED VARIATION OF INDUCTION MOTORS—SINGLE-PHASE MOTORS.

THE FIELD.

THE term induction motor is applied to all varieties of motor in which the equivalent of a rotating field is produced and made to act upon the turns of a short-circuited winding. Induction motors are designed for any number of phases in the supply or for single-phase supply. The single-phase machine needs special explanation and treatment, and it will not be further referred to until polyphase machines have been described. The reader is referred to pages 395 and 396 for an explanation of how a two-phase current may be utilised to produce a rotating field inside a ring. A similar explanation, but for a three-phase supply, is given in Fig. 527. Only three positions of the cranks are shown corresponding with instants 30 degrees apart (one cycle being 360 degrees). The reader should complete the diagram for himself to correspond with that on page 396. He should spare no pains to assure himself that the whole procedure is perfectly understood, for although the matter may seem a very simple one it is beset with pitfalls. The most elusive thing is a clear grasp of the absolute mutual independence of the time and space relations. It is on this account that they have been emphasised in the diagrams by representing each separately and also the two combined. The similarity in appearance of the time and space relations, arising from the use of *rotating* cranks, from which the *time* values are obtained, spaced 120 degrees apart, while the fixed *space relations* of the component field are also 120 degrees apart, is very liable to induce a superficial consideration of the matter and to result in vagueness of conceptions and faulty reasoning. The whole method used in building up the diagram may be equally well applied to any spacing of the coils, and its application to some unsymmetrical spacing is a good test of one's real grasp of the conditions.

The results obtained in Figs. 342 and 527 are for a two-pole field only, and only apply physically to the field at the centre of the ring, for in practical cases the fields could not be represented by the simple vectors F_A, (Fig. 342) etc., but would spread and be non-uniform and fringing in character anywhere but at the centre. These results, therefore, although essential as laying a foundation for future work, must not be applied without modification to cases where the interior of the stator ring is filled with toothed-iron (the rotor), or where a multipolar field is used, necessitating a coil spacing of less than 120 degrees. The reduced coil spacing causes the vector addition to give a higher resultant, so that with a four-pole field the value rises from 1·5 to 1·9 and if the coils of the three phases were

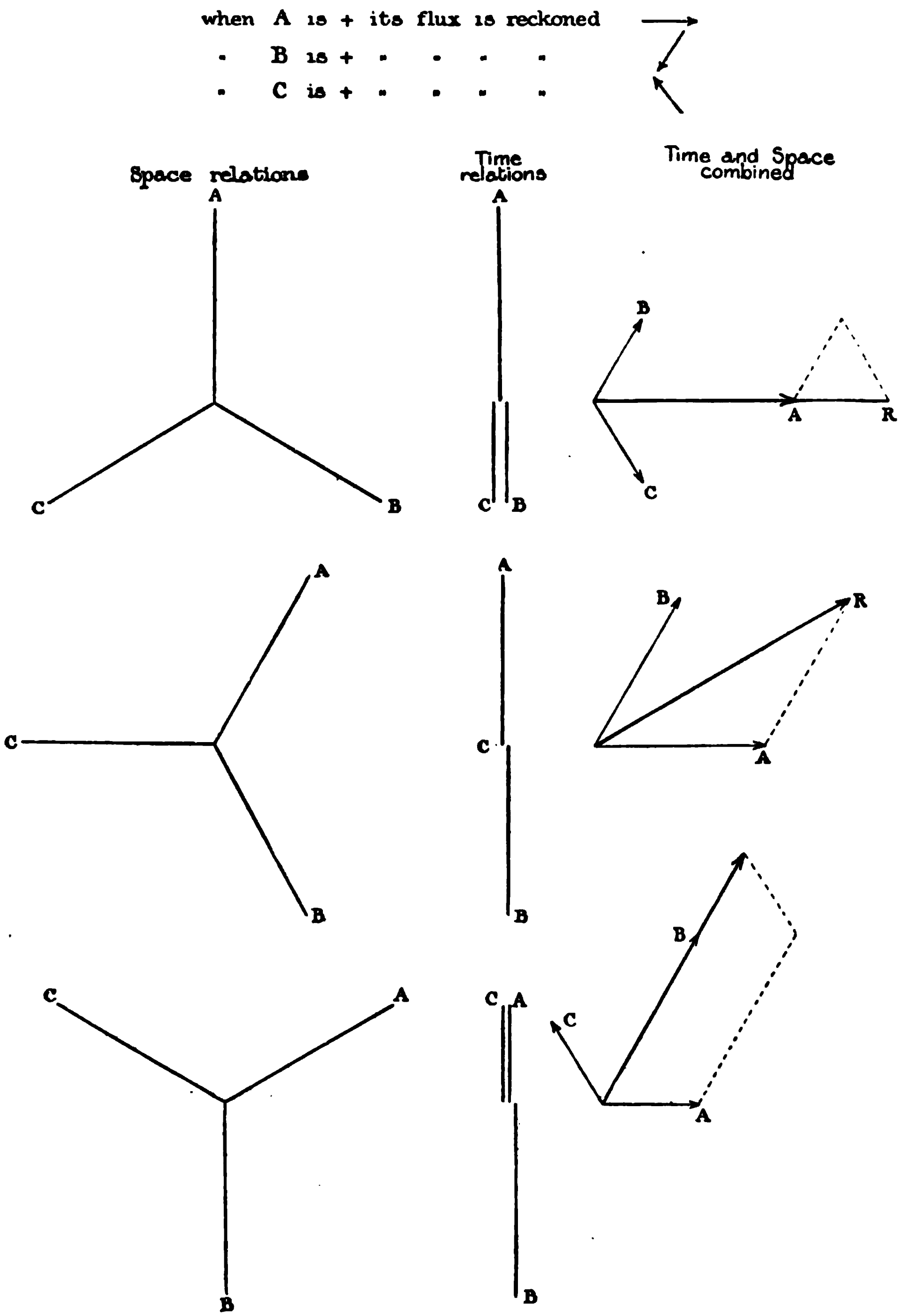


FIG. 527.—VECTORS SHOWING TIME AND SPACE RELATIONS OF THREE-PHASE CURRENTS PRODUCING A ROTATING FIELD.

coincident, so that they were wound one on top of another, the total would rise to 2. This last is not possible in motor practice, but may be quoted as referring to a straight iron core overwound with three coils of equal turns, carrying equal currents, which have three-phase time relations.

THE ROTOR.

If, having obtained a rotating field by two- or three-phase currents as described, a solid iron "rotor" be placed inside the field ring, the field will sweep round in the iron and will generate eddy currents in it which will pull the iron round after the field as explained in Chapter IV., Section VII., page 512. A glance at Figs. 165 and 166 (page 234) will establish the existence of a pull, for the currents in the lower half of Fig. 166 are producing a N pole above the copper sheet while those in the upper half are producing a S pole. The lower half will be repelled and the upper attracted by the magnet (Fig. 165), and the sheet will tend, therefore, to be dragged after the magnet. The same result will be arrived at by considering the currents immediately under the pole with reference to the rules for direction given on page 230.

As a matter of fact, the earliest experiments in the construction of rotors, notably those by Mr. C. E. L. Brown, included tests on rotors of solid iron, of laminated iron, of very thick copper cylinders, and of iron enclosed in a thin copper external sleeve. Experience has, however, resulted in the universal practice of confining the currents to copper windings carried in slots between the teeth on a laminated iron cylinder. The advantage of using laminated iron to prevent eddy currents in the iron masses and of providing lightly insulated instead of bare copper windings for the working currents, is that the currents are constrained to pass along predetermined paths and give as a result a better turning effort with somewhat less heating than when left to take merely the path of least resistance, as they would in a copper sleeve or solid iron rotor.

A very important point to be kept constantly in mind when considering the behaviour of an induction motor, is the fact that the rotating field revolves at a uniform rate from the moment current is switched on to the stator, provided always that the frequency of the supply main or generator remains unaltered. The speed of rotation of the field, then, depends entirely upon the frequency of supply, a point on which the reader may readily satisfy himself by a consideration of the diagram in Figs. 527.

If we consider what occurs at the moment of switching on we see that the field immediately begins to revolve at its full speed while the rotor is, of course, stationary, and the rotor windings, which frequently consist of solid copper bars, therefore become the seat of alternating E.M.F.s, since north and south poles alternately sweep past them, the frequency of these alternations while the rotor is stationary being the same as the frequency of the supply circuit. The rotor bars, however, are, in small motors (and they are all we need consider for the moment) all short circuited at each end of the rotor body, being sweated into substantial copper rings. The E.M.F.s in the bars, therefore, give rise to very heavy currents of the nature and general character of eddy currents, but constrained, as has just been pointed out, to follow defined paths, namely, along the bars. Since the magnitude of the E.M.F.s in the bars depends upon the rate of cutting, the greatest E.M.F. will be generated when the rotor is standing still, since under these conditions the field sweeps past it with the greatest relative velocity. So soon however as the rotor, answering to the pull between the currents in the bars and the field, begins to move in the direction of rotation of the field, the relative velocity of the field to the bars begins to fall off; the faster the rotor runs the greater is this falling off, and with the decrease in relative velocity (between rotor and field) two changes occur in the rotor currents. These two changes have opposite effects upon the magnitude of the rotor currents, for on the one hand the E.M.F.s driving the currents decrease while on the other the frequency of alternation of the currents also decreases. Considering that the rotor bars are all of copper of heavy section embedded in iron, it will be seen that their resistance is very small in comparison with their coefficient of self induction, and hence a decrease in frequency will tend towards an increase in current, owing to the diminution in the value of pL. A more careful examination into the relative magnitudes of the two effects just mentioned is unnecessary here, but it is important at the outset to realise this decrease in frequency and decrease in E.M.F., and to see that so far as magnitude of current is concerned the tendency of the two causes, in their effect on the current strength, is in opposite directions. When the speed of the rotor approximates to that of the revolving field, the value of pL becomes less important in comparison with the value of R (the resistance of the rotor bars). The falling off of E.M.F. when in the neighbourhood of full speed, produces an effect which overbalances the falling off of frequency, consequently as the speed of the rotor increases from, say, about 80 per cent of the field speed upwards the currents steadily decline. Between standstill and about 80 per cent of full speed the currents begin by rising as the speed runs up, and reach a maximum at some particular speed, after which the continued rise of speed is accompanied by a reduction in current strength.

As mentioned on page 512, Section VII., there must always be some "slip," that is, the rotor will not run so fast as the revolving field in the stator. This slip may be written as

$$\frac{n_s - n_r}{n_s}$$

where n_s and n_r are the speeds of the field and of the rotor respectively. The slip depends upon the load, and in a modern machine of 10 horse-power or upwards varies from about 2 per cent. on no load to 6 per cent. or 8 per cent. on full load, so that an induction motor is to all intents and purposes a constant speed machine.

ELEMENTARY NUMERICAL RELATIONS.

If the rotor windings are open-circuited the stator windings will behave like the windings of a choking coil into whose magnetic circuit a very small air gap has been introduced, for the air gap between the rotor and stator is generally cut down to the smallest permissible limits with regard to the mechanical requirements. Under these conditions the current in the stator windings will be determined by the same relations as have already been pointed out for the primary circuit of a transformer with an unloaded secondary, and when full voltage is switched on will clearly rise until it reaches such a value as will produce a sufficient flux to generate a back E.M.F. in the stator windings approximately equal to the terminal E.M.F.

The E.M.F. now generated in the rotor windings will have at any point in the circumference a value which can be written

$$e = \mathrm{B} \times l \times v \times 10^8 \text{ volts}$$

where e is the voltage induced in one rotor bar or wire, B is the flux density at that part of the rotor and at that instant, l is the length of the bar and v the velocity of the field relatively to the bar, all in centimetre measure. The total E.M.F. in one phase of the rotor will be the sum of all these values for the number of bars in series, the values will be different for different bars, since B is different at different parts of the circumference. The distribution of field is commonly taken as sinusoidal, so that the sum of the successive values of *e* is the area under a sine curve. It is of the utmost importance for a student to grasp the fact of this space distribution of the flux and to see that, since the velocity of the field (relatively to the rotor) is the same at all points, the values of *e* will follow the same law in their *space* relations. Now since the rotation of the field is uniform, the *time* relations of the values of *e* will also be sinusoidal. Hence there are two facts to be clearly borne in mind (*a*) that at any *one instant* the space distribution of E.M.F. round a rotor is sinusoidal, and (*b*) that in any *one bar* or wire, the variation of E.M.F. with time is sinusoidal.

We now proceed to consider what happens if the circuit of the rotor windings is closed, the rotor being then stationary.

The sinusoidal E.M.F. would set up sinusoidal currents. If the winding is a short-circuited one of the squirrel cage type, the currents will have *space and time* relations of a sinusoidal kind. If the rotor is a "wound" rotor having definite phases, then the current in all bars or wires belonging to one phase will be the same at any instant, and it is this which will determine the space distribution of current.

The time relation is clearly sinusoidal. The frequency depends, as has already been pointed out, upon the relative speed of field to rotor. If then the currents in the rotor corresponded precisely with the E.M.F.s generated by the field, the largest current would be where the field was strongest, and there would therefore be all the factors of high torque. The currents, however, lag behind the induced E.M.F. owing to self-induction, with the result that the strongest currrent is not in the strongest field and the torque is reduced by the lag. If the lag were a full 90 degrees the torque would sink to zero. Hence, we see the value of inserting resistance at starting, for, though it reduces the current it also reduces the angle of lag, and effects on the whole an increase in the starting torque. It is easy to see that this can be carried too far, and the resistance inserted must not be so large that the diminution in current strength outweighs the effect of the increase in $\cos \phi$.

HEYLAND DIAGRAM.

One of the most useful and practical of vector diagrams used by the designer is that evolved by Mr. Alexander Heyland, which embodies all the magnetic and electrical quantities, both in phase and magnitude, in a polyphase induction motor. By its use, from a few simple tests, the performance of a motor on all loads can be predicted within the limits of practical requirements, and the lines upon which to design a motor to fulfil any given conditions with regard to overload capacity or power-factor are at once indicated. The diagram can also be used to predict the performance of any motor by calculation, before any tests have been made upon it. An induction motor is analogous to a transformer, the primary being the stator winding, and the secondary being the rotor winding. The main difference between the induction motor and the transformer is the presence in the former of an air gap in the magnetic circuit between the primary and secondary windings. This, of course, greatly increases the magnetic leakage, and introduces important modifications into the transformer vector diagram to make it applicable to the induction motor.

Before proceeding to build up the complete diagram for any polyphase induction motor, it will be necessary to make a few preliminary assumptions. There are assumed to be no losses in the motor, and all the magnetic leakage is supposed to be confined to the stator.

The errors produced by these suppositions will be corrected for in the final diagram.

In Fig. 528, let O E be the E.M.F. applied to the stator terminals. As the stator windings are assumed to have no resistance, this line will also represent, but opposed in phase, the back E.M.F. of the stator. The stator flux which produces this back E.M.F. is therefore given by O D at right angles to O E, an E.M.F. always lagging 90 degrees behind the flux producing it. Let O C_s be the phase of the current taken by the stator, ϕ being the angle of lag of this current behind the applied E.M.F., O E. It is obvious that the leakage flux of the motor is produced by the stator current, that is, the stator ampere turns acting upon the reluctance of the leakage paths of the motor produce the leakage flux, which is therefore in phase with, and proportional to, the stator current. The leakage flux may be represented by O P. It then follows that D P must be the rotor flux, because it is the vector difference of O D, the stator flux, and O P, the leakage flux. Having obtained the rotor flux D P, the rotor E.M.F. can be set off at right angles to it at P Q, and as all the magnetic leakage is assumed to occur in the stator, the rotor can have no self-induction, and the rotor current must be in phase with the rotor E.M.F., and can therefore be set off along the line P Q to the same scale as the stator current. As in a transformer (neglecting no-load losses) the vector difference of the primary and secondary currents gives the magnetising current, so, in an induction motor, the vector difference of the rotor and stator currents also gives the magnetising current. Now the magnetising current of the motor is in phase with, and proportional to, the working or rotor flux, so that if a line O C_m be drawn from O parallel to D P, that is, at right angles to P Q, the current triangle O P C_m is at once obtained. O C_m is the magnetising current, O P the stator current, and P C_m the rotor current. At any load, it follows from the assumption that the rotor has no self-induction, that the angles D P C_m and O C_m P are right angles, and therefore that the loci of the points P and C_m are semi-circles, as shown in Fig. 529. From this diagram it is obvious that, the applied E.M.F. remaining constant, there are two limiting conditions:

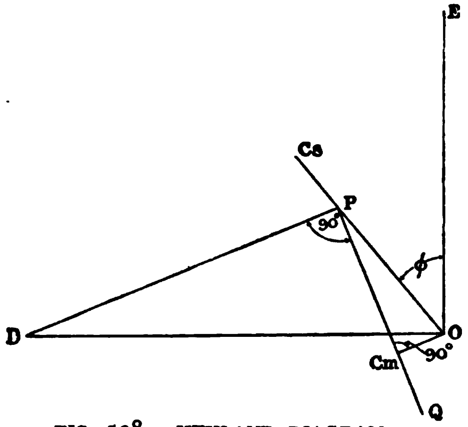


FIG. 528.—HEYLAND DIAGRAM.

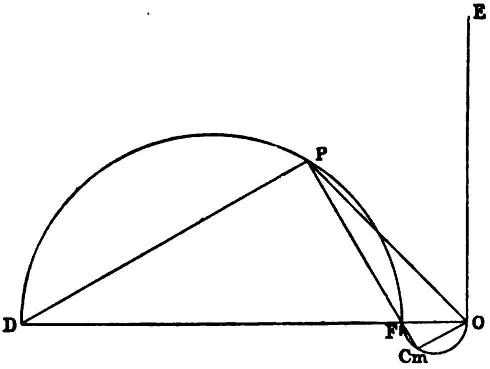


FIG. 529.—LOCI OF POINTS IN HEYLAND DIAGRAM.

(1) When the motor is running light.

(2) When the rotor is so overloaded as to be held stationary.

For convenience, let the stator flux be N_s, the rotor flux N_r, the leakage flux N_e, the reluctance of the leakage paths r, and that of the main magnetic path R. Also let C_s, C_r and C_m be the stator, rotor and magnetising currents respectively. In the first case, that of the motor running light, there is practically no leakage flux ($N_e = O$), the point P falls on F, and C_m falls on F, making the rotor flux equal to the stator flux, that is $N_r = N_s$. Now the rotor flux, N_r, is equal to the ampere turns provided by the magnetising current, that is, the stator current in this case, divided by the reluctance of the main magnetic path of the motor, or $N_r = N_s = \frac{OF}{R}$. In the second case, when the rotor is standing still, the point P moves around the semicircle until it falls on D, making the rotor flux N_r vanish, and making the leakage flux N_e equal to the stator flux N_s. The leakage flux N_e is equal to the ampere turns due to the stator current acting upon the reluctance of the leakage paths of the motor. That is $N_e = N_s = \frac{OD}{r}$.

Now, in the first case

$$N_r = N_s = \frac{OF}{R},$$

and in the second case,

$$N_e = N_s = \frac{OD}{r}.$$

N_s is the same in both cases, because the applied E.M.F. is constant,

$$\therefore \frac{OD}{r} = \frac{OF}{R}$$

$$\therefore \frac{OD}{OF} = \frac{r}{R}$$

This ratio $\frac{r}{R}$ is exceedingly important as determining the goodness of any given motor, for upon it depends the maximum power-factor and overload capacity obtainable. It is usually denoted by the symbol U, and called the "coefficient of utilisation of the motor." The reciprocal of U $\left(\frac{1}{U}\right)$ is generally called σ, and known as the "coefficient of magnetic dispersion."

Of course, the above results are based upon the assumption that the fluxes through any given part are proportional to the magnetomotive forces (the ampere turns) driving them. This is only true if the iron of the motor is not saturated, and in some types, such as those used for driving cranes and lifts, or for traction purposes, it would not be quite correct. However, it is generally sufficiently accurate for practical purposes. If, for any motor, the value of σ be known, its test curves can be predicted with accuracy. This is exceedingly convenient when dealing with large motors, which it would be very difficult to test on full-load in the shops. By means of a few simple measurements, which will be specified hereafter, σ can be obtained, and the diagram of the motor easily constructed. It is also possible to calculate from the mechanical dimensions and windings of a motor, what the value of σ will be, and the diagram and test curves of the motor can thus be plotted before the motor is built. A method by which the value of σ can be predetermined will be given later in this chapter. We are now in a position to construct the complete diagram, and to correct it for all losses. To simplify calculations, it is better to work with some of the quantities per phase, such as voltage and current, and to so adjust the scales of the other quantities that total input, torque and horse-power can be read off. In Fig. 530 O E is, as before, the applied E.M.F.; O P is the stator current, which can be split up into two components, one being O F, the magnetising current, the other P F, the component required to balance the rotor current; P F thus represents to some scale the rotor current itself. The input in true watts to the motor, at a stator current of O P amperes per phase, and an applied voltage of O E per phase is given, in a three-phase case, by the equation—

$$\text{Input} = 3 \times OE \times OP \times \cos\phi$$

$$\text{But } \cos\phi = \frac{PQ}{OP}$$

$$\therefore \text{Input} = 3 \times OE \times OP \times \frac{PQ}{OP} = 3 \times OE \times PQ.$$

Now $3 \times OE$ is a constant,

$$\therefore \text{Input} \propto PQ.$$

The point P could have been taken anywhere on the semicircle F P U D, and it follows, therefore, that all such perpendiculars from the outside circle to the base line, O D, are proportional to the input, Having obtained this result, the next step is to see how to obtain lines proportional to the torque and horse-power of the motor. If there were no losses at all in the motor its output would be equal to the power supplied to it, and the line P Q would represent torque and horse-power as well as input; such is not, of course, the case. The torque of the motor is proportional to the product of the rotor flux and rotor current; thus, if there were no drop of volts due to the current traversing the stator windings, it would be proportional to $DP \times PF$. The stator copper drop, however, results in a diminution of the stator flux, because the stator windings have to generate a back voltage which, vectorially added to the copper drop, is equal to the applied E.M.F. The larger the copper drop, therefore, the less back voltage the stator has to generate, and the required flux is correspondingly less. This diminution of stator flux of course occasions a proportional decrease in the rotor flux, which must be taken into account. The exact value of the diminution of stator flux need not be calculated, but the decrease of the rotor flux can be taken into account by deducting from the line, D P, a piece, P G, representing, in flux strength, the volts lost by the *load* component, P F, of the stator current. The drop occasioned by the magnetising component will be taken account of when correcting for the no-load losses. The point, G, can also be determined by subtracting from the line, P Q, a piece, P X, equal to the stator copper loss ($C^2 R$) in watts, and through X, drawing a line parallel to the base line, O D, and cutting D P at G. The same result is obtained whichever method is used. A circle can now be described, passing through D, G, and F. This will have its centre, c', perpendicularly below c, the centre of the outside circle, F P U D. The torque of the motor is now proportional to the product of all such lines as D G, the true rotor flux, and P F, the rotor current.

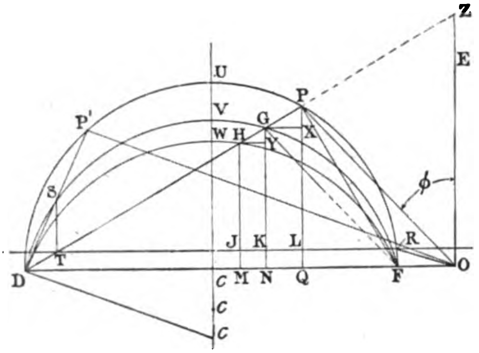


FIG. 530.—COMPLETE HEYLAND DIAGRAM.

Now

$$\text{Area of } \Delta DGF \propto DG \times PF$$
(base × height),
$$\text{and Torque} \propto DG \times PF$$
$$\therefore \text{Torque} \propto \text{Area } \Delta DGF.$$
$$\text{But Area of } \Delta DGF \propto FD \times GN$$
(base and height).
$$\therefore \text{Torque} \propto FD \times GN,$$
But F D is a constant,

$\therefore$ Torque $\propto$ G N, neglecting no-load losses.

The correction for the no-load losses can with advantage be introduced here. The no-load losses are composed of

(1) Stator and rotor iron losses.
(2) Friction of bearings and windage.

(3) The no-load current traversing the stator windings.

Of these the stator iron loss is by far the most important. That the sum of these losses is practically constant at all loads is obvious when consideration is taken of the fact that, although the rotor iron loss increases slightly on load owing to the increased frequency of magnetic alternation in the rotor produced by the increased slip, the stator copper drop results in a slightly smaller total flux, and therefore a diminished stator iron loss. The variation in the friction and windage losses from no load to full load is imperceptible. Thus, if a line be drawn across the diagram parallel to O D, and at a height, F R, above it equal to the no-load losses to scale, the perpendicular, G N, representing torque, is diminished by a piece, K N, equal to the no-load losses, and the line G K gives the true torque available at the motor shaft. The true no-load current can also be obtained, as it is the vector sum of the magnetising current O F, and the energy current F R required to supply the no-load losses. It is, therefore, given both in magnitude and phase by the line O R.

The horse-power of the motor is proportional to the product of the torque and speed. If there were no rotor copper loss, the motor would run at synchronous speed at all loads, and the horse-power would be proportional to the torque. The rotor copper loss, however, occasions a drop in speed, technically known as the "slip" of the motor, which is the same percentage of the synchronous speed as the rotor copper loss is of the total watts supplied to the rotor by the rotating magnetic field. The rotor copper drop can therefore be corrected for in a similar way to the stator copper drop. A piece, G H, corresponding to the rotor copper drop, is marked off down the line G D, and the point H is obtained, or a piece, G Y, equal to the rotor copper loss in watts, is cut off from G N, the point H being found by drawing H Y parallel to O D, cutting G D in H. Again, as in the case of the stator correction, the same result is obtained with either method. Through the points F, H, and D a segment of a circle is now drawn, its centre, c'', being perpendicularly below c and c', those of the other two outer circles. Now, if from the point H a perpendicular, H M, be dropped on O D, the true horse-power output, after deducting the no-load losses, is proportional to the length of all such lines as H J. It is evident that as the point H is moved around the circle, there will come a time, P having reached the position P′, when the perpendicular H J will vanish, that is, the output in horse-power will become zero. This is the case when the motor is standing still. D P′ is, of course, a tangent to the inner circle, and at right angles to D c''. The perpendicular S T, from the torque circle on to the no-load loss line, gives the starting torque of the motor, this torque being given with a stator current of O P′ amperes.

The rotor current of the motor is directly proportional to the slip, because the larger the slip, the larger the E.M.F. in the rotor bars, and the larger corresponding current driven by it through the resistance of the rotor. Also, the slip varies inversely as the rotor flux, because if the flux be increased, the slip can be correspondingly diminished to keep a constant output.

Thus, slip $\propto \frac{\text{P F}}{\text{D G}}$.

Constructions for the slip are numerous, but are not very satisfactory in practice. They are usually only quite approximate, and for accurate work, the slip is best calculated from—

$$\text{Slip} = \frac{W_r}{W_r + (\text{HP} \times 746)}$$

where W_r = copper loss in rotor in watts, and HP = horse-power load on motor.

A rough graphical method of obtaining the slip, neglecting the stator copper drop, is as follows: Produce D P to cut O E at Z. Now, all such lines as O Z are approximately proportional to the slip, because, if the rotor flux be assumed to be equal to D P instead of D G, then

$$\text{slip} \propto \frac{FP}{DP} \propto \tan P\hat{D}F; \text{ but}$$

$$\tan P\hat{D}F = \frac{OZ}{OD}. \quad OD \text{ is constant.}$$

$$\therefore \tan P\hat{D}F \propto OZ.$$

$$\therefore \text{slip} \propto OZ.$$

Thus O Z is at any load a measure of the slip, neglecting the stator copper drop G P. The scale is fixed by producing D P′ to cut line O E. The part cut off on O E is 100 per cent. slip, because at the point P′ the motor is standing still. This completes the diagram for any polyphase motor, and it only remains to briefly indicate the tests necessary to give sufficient data for the construction of the diagram. First, run the motor light at normal voltage, and measure the no-load current and power factor. Next, with the rotor fixed, apply normal voltage, and measure the short circuit current and power factor. If this latter should prove too large, a measurement can be made with a reduced voltage, the current obtained being increased in the ratio of the normal voltage to that actually used. This gives results quite accurate enough for practical purposes, as the impedance of the motor does not vary largely with the applied voltage, unless the motor be very saturated. The only further measurements required are the stator and rotor resistances per phase. From the no-load reading, the line O R is obtained, and from the short circuit reading, the line O P′ can be set out. A circle can now be drawn passing through R and P′, with its centre on the base line, O D. At any load, the stator and rotor copper drops, P G and G H, can be calculated, and the torque and horse-power circles can be inserted. All that now remains to be done is to draw through R a line parallel to O D. This is the no-load loss line, and, on the insertion of the perpendiculars P L, G K and H J, the diagram is complete. By taking a number of points, P, P_1, P_2, P_3, etc., the full test curves for the motor can be plotted.

PREDETERMINATION OF THE "DISPERSION COEFFICIENT," σ, OF A GIVEN MOTOR.

From the foregoing explanation of the general induction motor vector diagram, it is obvious that the value of σ is the chief factor in determining the performance of any given motor. This fact has led to many attempts on the part of designers to calculate with accuracy the value of σ from the mechanical and electrical data of a motor, but the problem is so complex that it is not possible, from theoretical considerations alone, to predetermine σ with any pretence to accuracy. By a combination of theoretical and practical investigation, however, formulæ and curves have been obtained which render possible the determination of it with sufficient accuracy for commercial design work. The method of calculation which we shall describe here is that given by Mr. Hobart, in his book, "Electric Motors," and is based upon the original method proposed by Mr. B. A. Behrend in his book on "The Induction Motor." The method has been found by the author to work extremely well in practice, if allowance is made when using it for any abnormal characteristics of the design to which it is applied.

The leakage flux of any given motor may be divided into three chief parts.

(1) Peripheral dispersion;

(2) End dispersion, including the self-induction field of the end connections;

(3) "Zig-zag" dispersion.

The first named is the leakage flux which passes from one pole to the other along the tops of the stator and rotor teeth, and therefore, of course, does not cut the rotor conductors. This is much diminished by using a large pole pitch, and is greater in a motor with closed slots than in one with open slots. The second is that flux which passes through the air from pole to pole at the ends of the motor, and also the self-induction flux around the end connections of the stator winding. This latter is much increased if the end connections are in close proximity to the iron of the stator housing or core. The "zig-zag" leakage flux is so called because it passes peripherally along a stator tooth, crosses the gap, passes along the top of a rotor tooth, crosses the gap again, and so on until it reaches the adjacent pole.

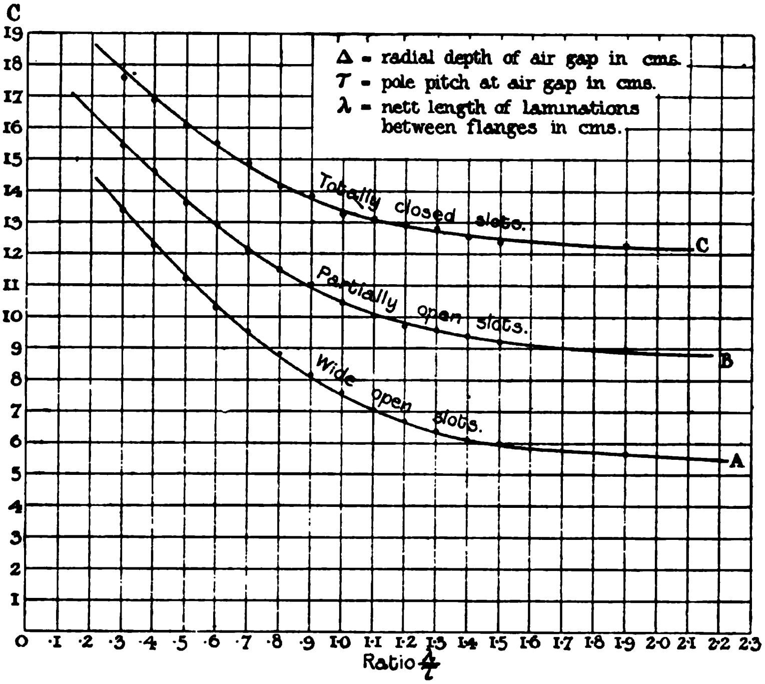


FIG. 531.—VARIATION OF C WITH $\frac{\lambda}{\tau}$

The formula originally used by Behrend takes account chiefly of the peripheral dispersion, almost neglecting the end dispersion and self-induction of the end connections, though these may readily be of overwhelming importance. It also overlooks the "zig-zag" dispersion. The original formula is

$$\sigma = C\frac{\Delta}{\tau}$$

where Δ = radial depth of air gap (in cms.); where τ = pole pitch at air gap (in cms.); and C = a constant, depending, according to Behrend, upon the shape and size of the slots, and many other things. It is obvious that if the value of C is only varied with the shape and size of the slots, the formula only takes account of the peripheral dispersion. To allow for end dispersion and self-induction of end connections, it is necessary to know how C varies with the ratio $\frac{\lambda}{\tau}$, λ being the net length of the laminations between end plates.

Hobart has therefore prepared a curve for open and closed slots, showing how C varies with this ratio $\frac{\lambda}{\tau}$. These curves are reproduced in Fig. 531. Most modern motors are built with partially open slots and to allow for the effect of these, curves may be drawn between those for wide open and completely closed slots. The formula now takes account of all except "zig-zag" dispersion, and this is finally allowed for by introducing a second constant C′, depending upon the product of H, the mean number of slots per pole on rotor and stator, and Δ, the radial depth of the air gap in centimetres. It is evident that the larger the number of slots per pole on rotor and stator, and the larger the air gap, the less will be the "zig-zag" dispersion. A second curve is therefore provided (Fig. 532) giving values of C′ plotted against H × Δ. The final formula is now

$$\sigma = C\,C'\,\frac{\Delta}{r}$$

and both C and C′ can be obtained from the curves. In the case of squirrel cage rotors, the value of σ as calculated above may be multiplied by another factor, a good average value of which is ·75, because, owing to the end connections consisting of only one conductor, the self-induction flux is much reduced. In exceptional circumstances, such as obtain in a high-voltage motor with a large number of turns, and in one whose end connections are placed near to the iron of the stator core or frame, higher values of σ may be expected, but for good ordinary designs the foregoing formula enables σ to be predicted with surprising accuracy.

CONSTRUCTION OF INDUCTION MOTOR.

Before going any further it would not be out of place to illustrate the component parts of an actual motor of the induction type so as to obtain an insight into the usual construction of such a machine.

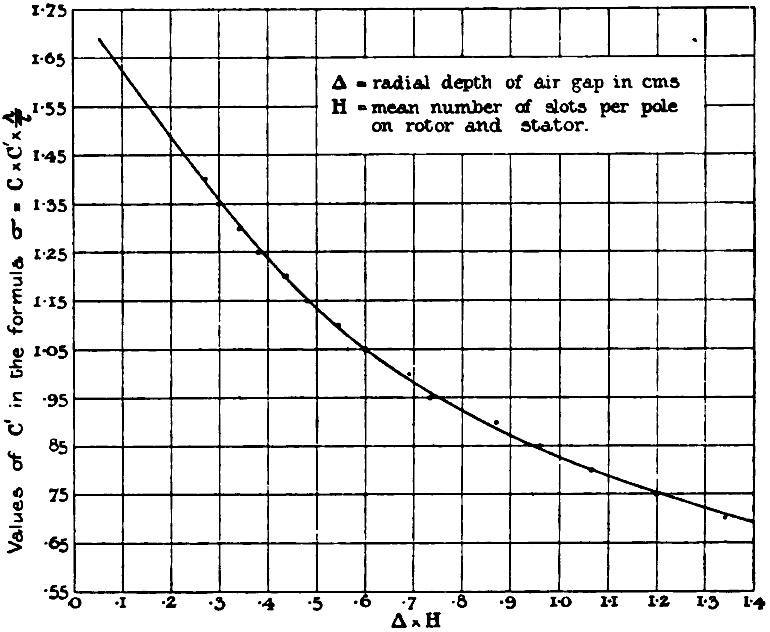


FIG. 532.—VARIATION OF C′ WITH Δ × H.

THE STATOR.

Fig. 533 shows the stator of an induction motor ready to receive the windings. The annular core is built up inside the cast iron frame and clamped by a substantial end ring. This core is slotted to receive a polyphase winding, two- or three-phase as the case may be. It will be noticed that the slots are nearly *closed*, this being the most usual practice; when the laminations of thin iron forming the core are assembled the slots are completely closed, but after boring (owing to the short air-gap boring is always necessary), the slots are partially opened by sawing through the thin bridge of iron with a hack saw.

Completely closed slots were used in the early days, and sometimes completely open slots (to receive former-wound coils), but for the reasons mentioned above and further explained later, the almost universal practice is to employ nearly closed slots.

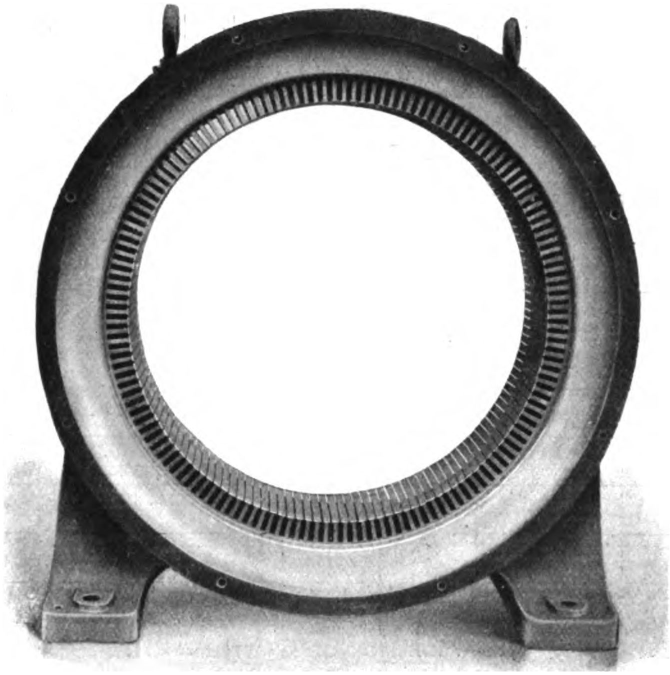


FIG. 533.—UNWOUND STATOR CORE.

STATOR WINDINGS.

As regards the windings, the stator winding and also the number of slots in the stator will be determined in the first place by the speed and frequency of the supply, and also, of course, by the number of phases for which it is to be wound. The method of determining a suitable number of slots and winding for a special case will be given later.

The actual stator windings, are very similar in nature to the windings for polyphase alternators, with which we have already dealt. The number of poles which the windings must produce will, of course, be fixed by the prescribed frequency and desired speed exactly as in the case of the alternator, and it is simply a question then as to how the coils will be wound, *i.e.* whether in a given case they will be of the double coil or single coil type; and here the same considerations hold, that is, for a two-phase motor the single coil windings will be the simplest, and for a three-phase motor the double coil windings are generally adopted for reasons already explained.

In Fig. 534 is shown the stator complete with windings in position, but with its end plates removed; it will be seen that the winding is of the double-coil type (this being a stator for a three-phase machine), and since it is wound in nearly closed slots it would have to be a hand winding; that is, a length of wire long enough to wind a whole coil would be taken, and this would be passed through the slots by hand until the slots were filled up with the right number of turns of wire. For low voltage work it is usual to line the slots with presspahn or similar material, the wire employed being either braided or served with a heavy double cotton covering, and, of course, care must be taken not to abrade the wire during winding. For

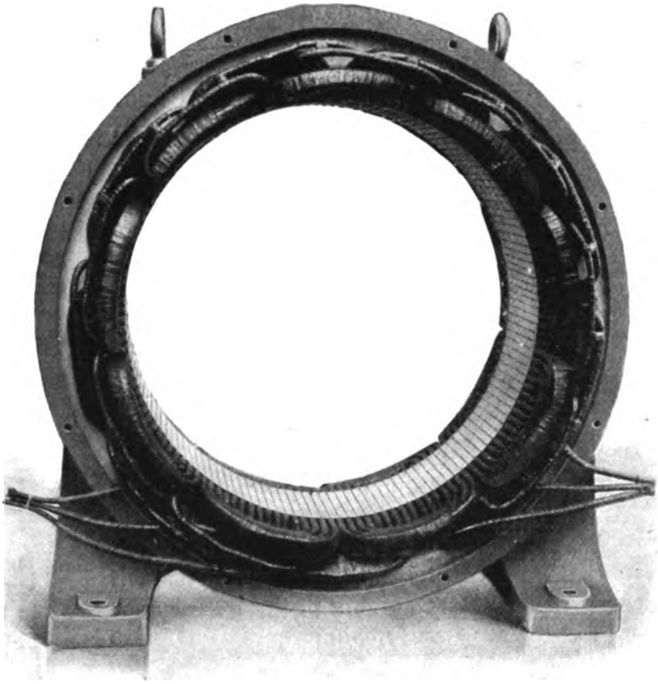


FIG. 534.—WOUND STATOR CORE.

high-voltage motors, micanite tubes are employed, and care is taken, in winding, to lay some flexible insulating material, such as empire cloth, between the various portions of the winding at those points where any considerable voltage may exist between adjacent conductors in the same slot. In the stator shown the slots are lined with presspahn and mica tubes so as to enclose the coils in passing through the iron core ; the bent ends of the coils are taped over for protection from contact and to give them rigidity.

THE ROTOR.

Fig. 535 shows an unwound rotor. The stamped core discs are threaded on the spider, and an end ring, held in position by four bolts, completes the construction. The rotor slots, it will be seen, are nearly closed, and the same remarks concerning the openings apply here as in the case of the stator. The rotor may be of the "squirrel" cage or "wound" type.

The "squirrel" cage construction, an example of which is shown in Fig. 536, consisting merely of substantial copper or brass bars thrust through the slots in the rotor core and short circuited together at each end by massive end rings, has much to recommend it from the mechanical standpoint. There is nothing to go wrong short of an actual fusing of the copper bars or damage to the soldered joint where the bars are connected to

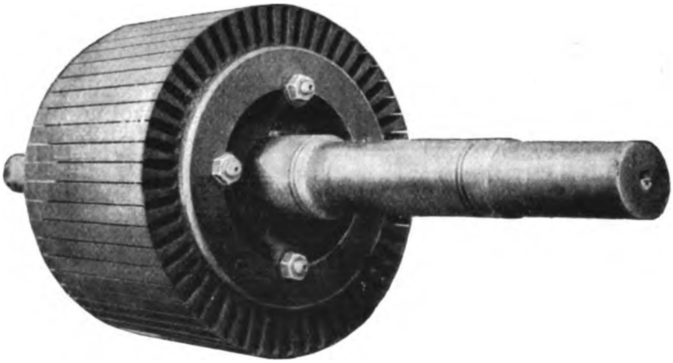


FIG. 535.—UNWOUND ROTOR.

the end rings, but such rotors are used only to a limited extent in Europe though they are used far more extensively and in larger sizes in America; the limitations of the squirrel cage rotor will be touched on later.

The wound rotor is more frequently used; and generally, with these rotors, the ends of the winding are brought to slip rings on the shaft, so that an external starting resistance may be employed, which improves the starting conditions of the motor from every standpoint.

Figs. 537 and 538 show two forms of wound rotor, Fig. 537 being wound with many turns of comparatively thin round wire, while Fig. 538 is wound with stout bars of copper. In each of the rotors shown the slip rings are arranged to be on the same side of the bearing as the rotor and, consequently, within the motor casing; but this is not always the case, the connections from the rotor being often carried through a hollow shaft to the further side of the bearing; and there fixed to slip rings. This device admits of a more compact design of motor.

We may mention at once that all wound rotors have three-phase windings whether the motor is a two- or three-"phaser," and for a very simple reason, viz. that the three-phase winding only requires *three* slip rings, whereas a two-phase winding would require *four*, and there is no electrical disadvantage in employing such a *three-phase* wound rotor in a *two-phase* machine.

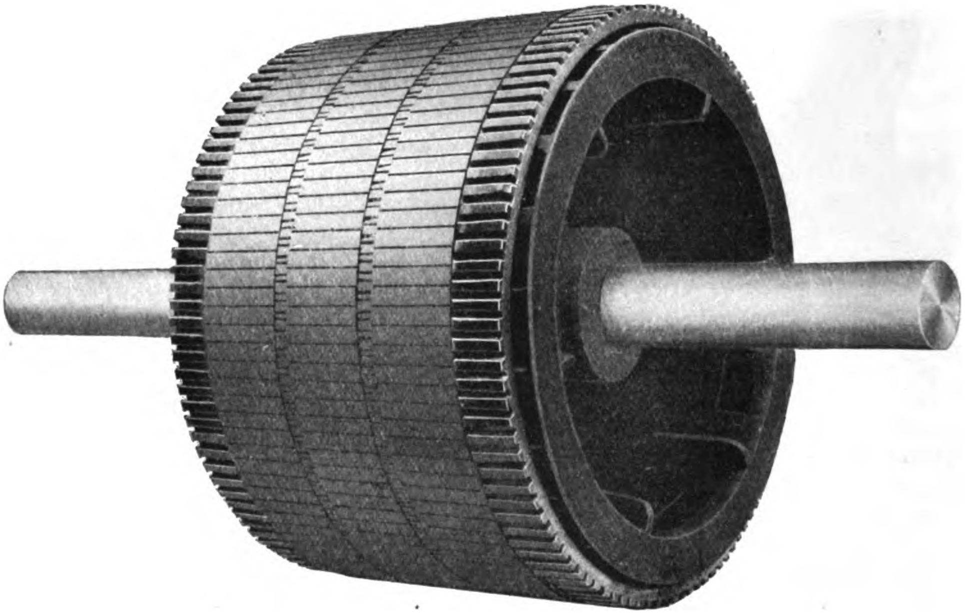


FIG. 536.—SQUIRREL-CAGE ROTOR.

CHOICE OF ROTOR WINDING.

As is the case with continuous-current motors, the starting and running conditions must be prescribed before the most suitable type and design of motor can be decided upon.

An induction motor to give a heavy starting torque like a series-wound continuous-current machine will have to be somewhat differently designed to a motor required only to start up under a moderate load such as would be suitable for the shunt-wound continuous-current motor. Efficiency is likewise of importance, and with the alternating-current motor there is always the question of the *power factor* to be considered, as a motor running at a low power factor, especially if the power factor is very low at starting, may cause trouble by affecting the regulation of the line to a prohibitive extent, especially if the motor is of considerable size.

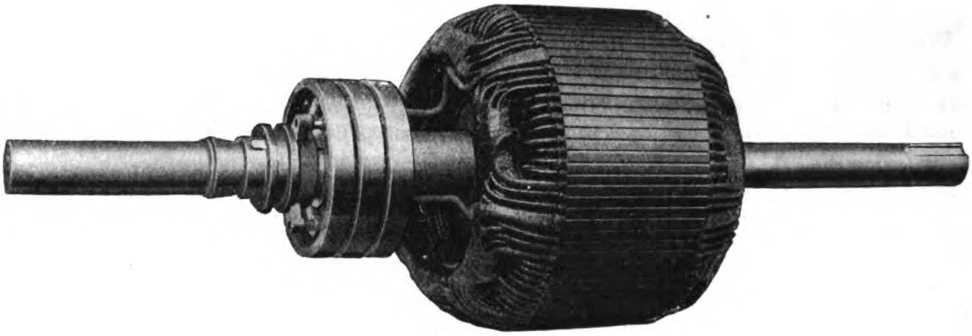


FIG. 537.—WIRE-WOUND ROTOR.

The choice of the type of rotor winding will generally be decided by the starting conditions and the size of the motor.

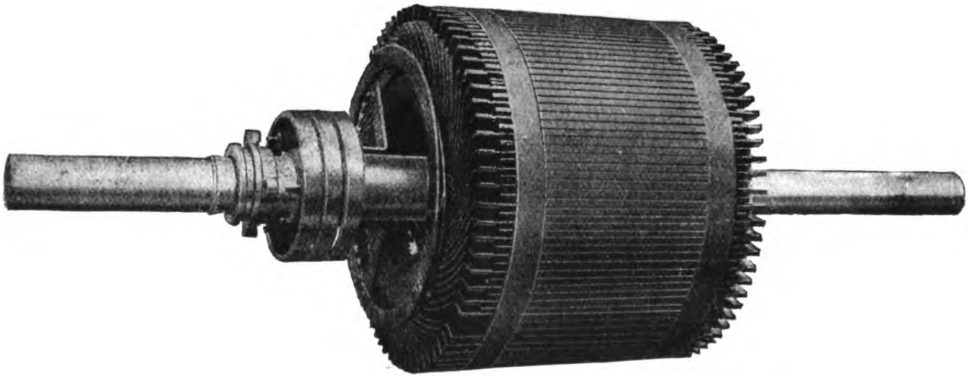


FIG. 538.—BAR-WOUND ROTOR.

The squirrel cage or short-circuited rotor is ideal mechanically, there is nothing to go wrong with the winding, and the full speed performance is better even than with the wound rotor; the construction is also cheaper. With regard to starting torque, however, the short-circuited rotor is at a great disadvantage compared with the wound rotor with external starting resistances.

To generalise, we may say that the short-circuited rotor is preferable for all *small* motors and for large motors where a heavy starting current and low power factor at starting are not a serious disadvantage as would be the case where power is supplied only for motor work, in which case fluctuations of the line pressure are not of such importance as they would be if lighting were attempted upon the same circuit.

Where it is necessary to obtain a very high starting torque, comparable in any way with the starting torque of the series-wound direct-current motor, resort must be made to the wound rotor, for it is virtually impossible, even if moderately heavy starting currents and low power factor are not an objection, to obtain any large starting torque from the squirrel cage rotor, except in the case of the very smallest size motors, where by special design fairly high starting torque can be obtained, but then only at the expense of efficiency under normal running conditions.

It is the practice in Europe to use wound rotors for all motors above 5 horse-power, but as stated above, in America short-circuited rotors are frequently used in much larger motors, because in most cases the polyphase currents are generated for power purposes only, there being few lighting circuits to be interfered with.

Induction motors are built in sizes ranging from less than a horse-power up to some hundreds of horse-power, and may be built for voltages as high as alternators may be, indeed, there appears to be no limits to the size and voltage of an induction motor except those which apply to three-phase alternators, but induction motors are not commonly built in sizes of more than 200 horse-power.

INDUCTION MOTOR DESIGN.

The size of an induction motor for any given output is fixed chiefly by two considerations, viz. temperature rise allowed, and overload capacity, or power factor, required. In the case of a continuous-current motor or dynamo we have seen that reasonable heating and absence of sparking were the indications of a satisfactory design; with an alternator, temperature rise and voltage drop were the limiting factors, and we now see that, although heating continues to be of importance, the place of sparking and voltage drop is taken by overload capacity or power factor. All these last-named are dependent on self-induction, which itself depends on the magnitude of certain stray or leakage fluxes.

The size of the motor can be obtained from an experimental curve of

$$\frac{\text{B.H.P.}}{d^2 l \times \text{R.P.M.}}$$

plotted against output in B.H.P., where

d = internal diameter of stator in inches.

l = gross length of rotor or stator core in inches.

R.P.M. = Revolutions per minute.

B.H.P. = Brake horse-power.

Such curves are shown in Fig. 539 both for small motors up to 70 brake horse-power, and for large ones up to 350 brake horse-power. In order that the method of design employed may be easily followed we shall illustrate each step taken by going through the design of a three-phase motor constructed by Messrs. Johnson and Phillips, of Charlton, of which the specification runs as follows :—

Three brake horse-power, 1,500 revolutions per minute, 50 ∿ three-phase **Y**-connected, $\frac{380}{220}$ volts, overload capacity 2 η not less than 80 per cent., cos ϕ not less than ·85, short-circuited rotor.

This of course means 3 brake horse-power, 1,500 revolutions per minute (synchronous speed), frequency 50 cycles per second, three-phase star connected, 380 volts across the line and 220 volts per phase, overload torque which the motor will stand before pulling up, not less than twice the normal running torque, efficiency not to be less than 80 per cent., power factor not to be less than ·85, and the rotor to be squirrel cage. The first step necessary in the design is to determine from the curve the value of C. Having obtained this, the speed and output being known, d^2l can at once be found, for

$$C = \frac{\text{B.H.P.}}{d^2l \times \text{R.P.M.}}$$

$$\therefore d^2l = \frac{\text{B.H.P.}}{\text{C} \times \text{R.P.M.}}$$

For this particular motor C = ·0000103

$$\therefore d^2l = \frac{3}{\cdot0000103 \times 1500} = 193\cdot5.$$

All manufacturing firms have standard sizes of induction motors, the diameters increasing from about 4 in. by increments of a few inches up to the larger sizes, while the lengths are generally variable by using more or less of the stampings which compose the stator and rotor cores. It is, therefore, generally the procedure to select a likely diameter, and work through a trial design to determine whether the specification can be complied with as regards overload capacity, power factor, efficiency and heating. If this cannot be done another diameter is chosen and a second design worked out. In our case one of the standard diameters is $6\frac{3}{4}$ in., and a tentative design will be worked out with this as a basis, as d^2l has been found to be 193·5, and $d = 6\frac{3}{4}$ in., $l = \frac{193\cdot5}{6\cdot75^2} = 4\cdot25$ in.

From the prescribed synchronous speed and the frequency the requisite number of poles can be determined, for

$$\frac{\text{R.P.M.}}{60} \times \frac{p}{2} = \sim,$$

where R.P.M. = revolutions per minute,
p = number of poles,
$\sim$ = frequency.

In our particular case

$$\frac{1500}{60} \times \frac{p}{2} = 50,$$

$$\text{whence } p = \frac{50 \times 60 \times 2}{1500} = 4.$$

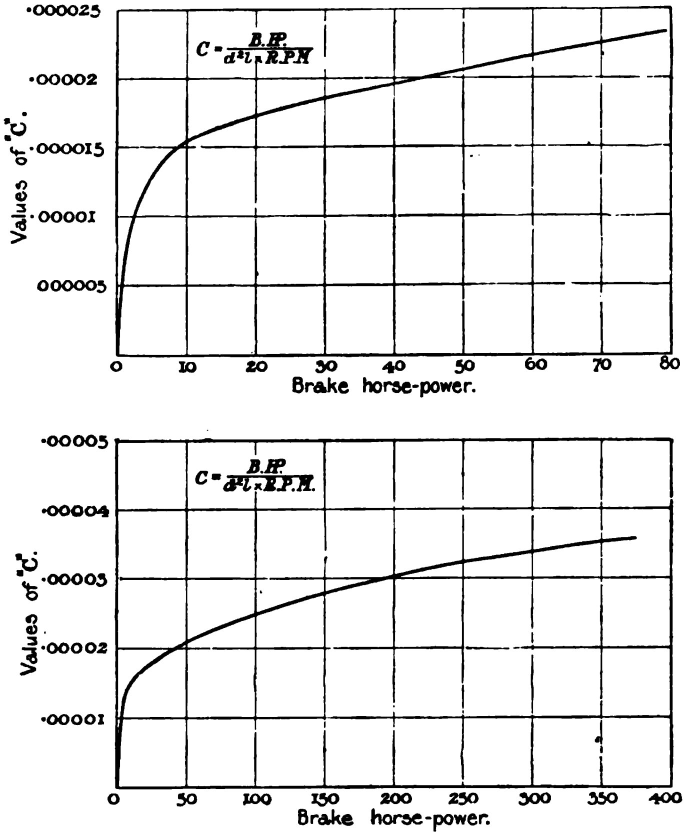


FIG. 539.—CURVES CONNECTING SIZE AND OUTPUT.

The pole pitch at the stator face, τ, can now be found. This is of course equal to $\frac{\pi d}{p}$. In this case $\tau = \frac{\pi \times 6\cdot75}{4} = 5\cdot3$ in.

The method of proceeding with the design from this point depends upon whether a standard carcase with a given number and size of rotor and stator slots is to be used, which is generally the case in commercial work, or whether the number and dimensions of the slots are open to choice. The total number of slots used depends upon the number of slots per pole per phase chosen, and except in special cases, such as those of high-speed motors of fairly large diameter and low frequency with a large pole pitch, the number generally used is three.

Thus, in the case under consideration, the total number of slots is 36, giving nine per pole and three per pole per phase.

There has been doubt among designers as to whether it is more advantageous to employ closed or open slots. When closed slots are used the bridge of iron which separates them from the gap is made very thin; but even then the peripheral leakage is much increased and lower over-load capacity and power factor results. If the slots are entirely open, however, although former-wound coils can be used, which greatly simplifies winding, yet the very high gap density, and therefore the high magnetising current resulting, has prevented these from coming into general use. Another reason against the employment of open slots is that the stator and rotor cylindrical faces cannot be turned, which renders necessary the employment of larger air gaps than are used when both rotor and stator are accurately machined. It is the best practice to stamp completely closed slots in stator and rotor plates, and after the assembling and boring have been done, to cut through the thin iron bridge at the top of the slots with a hack saw, thus interrupting the continuity of the iron leakage path. The opening thus produced varies from $\frac{1}{16}$ in. to $\frac{1}{8}$ in.

The length of the air gap employed is the smallest compatible with mechanical safety, and depends on length between bearings, diameter of shaft, and diameter of rotor, and also upon the speed of rotation. In the motor under consideration the stator bore is 6·75 in. and the rotor diameter is 6·7185 in. giving an air gap of ·01575 in. a side.

The number of rotor slots is generally larger than that of the stator slots, and is so chosen that it has no common factor with the number of stator slots. This is done to prevent what is technically called "cogging." If the rotor and stator slots are numerically multiples or sub-multiples of one another, or even have a large common factor, there exists one position of the rotor relative to the stator in which a larger number of tooth faces are opposite one another than in any other position, giving an easier magnetic path for the main flux. The rotor therefore tends to remain in this position, and jerky running results. This can be obviated by choosing the rotor slots as before mentioned. In the case in question the number of rotor slots chosen is 49. We are now in a position to calculate σ, the leakage coefficient, by the method previously explained.

The formula is

$$\sigma = \mathrm{C} \times \mathrm{C}' \times \frac{\Delta}{\tau} \times \mathrm{C}'''$$

and to get the value of C and C′ we have to refer to the curves on page 587.

The ratio of $\frac{\lambda}{\tau}$ is first calculated, τ being the pole pitch and λ the net length of iron in core which is obtained, as there are no air ducts, by deducting ten per cent. from the gross length to allow for insulation between the laminations.

In our case, $\lambda = 3{\cdot}825$ ins. $= 9{\cdot}72$ cms., and $\tau = 5{\cdot}3$ ins. $= 13{\cdot}45$ cms., so that the ratio is $\frac{9{\cdot}72}{13{\cdot}45} = {\cdot}722$. On reference to the Fig. 531, taking a curve for slightly open slots near to the closed slot curve, we see that the value obtained for $C = 13·5$. To find C'' we multiply Δ, the depth of the air-gap in cms. by H, the average number of slots per pole on the rotor and stator, and refer to the second curve.

In this case

$$\Delta = ·4 \text{ mm. and } H = \frac{9 + 12·25}{2} = 16·625,$$

$$\Delta \times H = ·04 \times 10·625 = ·425,$$

and on taking the value of C' corresponding to this from Fig. 532 it will be found to equal $1·525$. The third constant, C''', is 1 for a wound rotor, and a good average value for a squirrel cage rotor is ·75,

$$\therefore \sigma = 13·5 \times 1·525 \times \frac{·04}{13·46} \times 75$$
$$= ·0458.$$

$\therefore$ U, the coefficient of utilisation,

$$= \frac{1}{\sigma} = \frac{1}{·0458} = 21·8.$$

We are now in a position to see whether the conditions of power factor and over-load capacity demanded in the specification can be complied with. We shall not repeat here an explanation of the Heyland diagram, and if the reasons for any of the operations performed are not quite clear from this description, the reader is referred back to the description of the diagram which has already been given. A study of this will elucidate any obscure points. If we draw a diagram, as in Fig. 540, making $OD = OC_m \times U$, where U is the coefficient of utilisation, erect a semicircle upon DC_m and a perpendicular O E at O, we have the basis of the Heyland diagram for the motor.

The next step is to draw a line from O, making an angle ϕ with OE, such that $\cos \phi = ·875$. The actual power factor asked for in the specification is ·85, but it is always well to allow in this preliminary stage a small margin of safety. This line from O will cut the circle at P, and OP is the primary current. The perpendicular PS gives the input and PD the rotor flux.

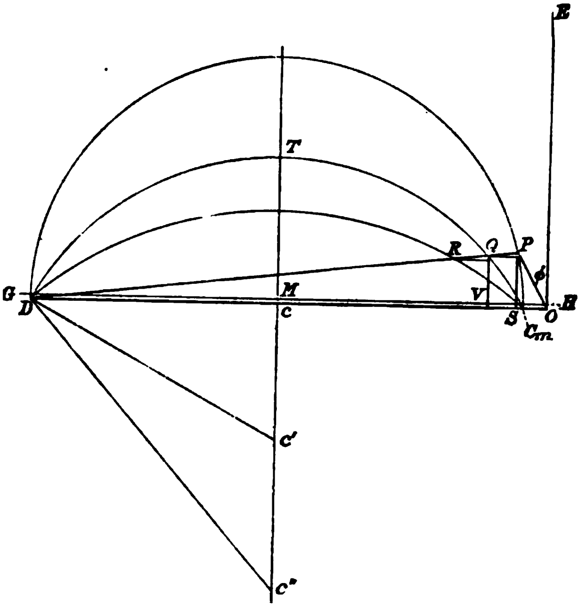


FIG. 540.—THE PRELIMINARY HEYLAND DIAGRAM.

Before we can proceed further, it will be necessary to roughly apportion the losses. From the specification, the efficiency is not to be less than 80 per cent. This means that the sum of the losses must not exceed 20 per cent. of the input.

$$\text{Input} = \frac{\text{B.H.P.} \times 746}{\eta}$$

In our case, this becomes

$$\frac{3 \times 746}{·80} = 2{,}800 \text{ watts.}$$

The output is $3 \times 746 = 2{,}238$ watts; the loss is therefore given $2{,}800 - 2{,}238 = 562$ watts.

The way in which this is divided between the stator and rotor copper losses and the iron friction and windage losses is a matter of experience. In this case, we will assume that our 20 per cent. loss is made up as follows :—

	Per cent.
Stator copper loss	6·4
Rotor „ „	6·7
Iron, friction and windage losses	6.9
Total	20·0

We can now proceed with the diagram, for if we subtract from P S, at the end marked P, a small portion equal to 6·4 per cent. of the length of P S, and through the point thus obtained draw a line parallel to O D, cutting P D at Q, we shall be able to draw the second circle of the diagram through D Q and C_m, with its centre perpendicularly below C, the centre of the first circle. To correct for the iron, friction and windage loss, a line G H is drawn across the diagram parallel to O D, and at a height *c* M, equal to 6·9 per cent. of P S, from it. A perpendicular Q V, from Q on to G H, gives the normal torque. The correction for the rotor copper loss can be applied in an exactly similar manner to that for the stator, by taking from Q V a piece equal to 6·7 per cent. of P S, and obtaining a point R through which the third circle can be drawn. The specification states that the maximum torque before pulling up is to be at least twice the normal running torque, that is, that T M is to be at least twice Q V. If the respective lengths of these lines be measured, it will be found that T M is 2·99 times Q V, so this part of the specification is amply complied with.

The current taken by any three-phase motor is given by

$$C = \frac{\text{B.H.P.} \times 746}{3 \times V \times \cos\phi \times \eta}$$

where V = voltage *per phase*.
and η = the efficiency.

In our case

$$C = \frac{3 \times 746}{3 \times 220 \times \cdot 85 \times \cdot 80} = 4\cdot 98 \text{ amperes.}$$

This is represented by the line O P, which is 2·5 units long, and we thus obtain a scale for current, which enables the magnitude of the magnetising current, OC_m, to be obtained. OC_m is ·98 units long, and therefore corresponds to

$$4\cdot 98 \times \frac{\cdot 98}{2\cdot 5} = 1\cdot 95 \text{ amperes.}$$

The magnitude of the magnetising current depends on the magnetic densities employed in the various parts, but chiefly on that used in the gap.

This in turn depends on the number of turns of winding used on the stator. If, therefore, we employ such a number of turns that a magnetising current of 1·95 amperes is obtained, the motor will conform to the specification both as regards power factor and overload capacity. Before proceeding to the calculation of the number of turns required in the stator winding, it will be necessary to point out the similarity existing between the induction motor and the alternating current transformer. The induction motor very much resembles a transformer with an air gap in its magnetic circuit, the stator usually corresponding to the primary, and the rotor to the secondary. The stator has a back E.M.F., and takes a no load current which is the resultant of magnetising current and no-load loss current, in exactly the same way as a transformer. The voltage induced in the rotor depends exactly on the ratio of the numbers of rotor and stator turns, and with one slight modification, the formula connecting voltage and flux for the transformer applies for the induction motor. The induction motor formula is

$$E = \frac{4\cdot 44 \, N \times t \times \sim \, k}{10^8}$$

where E = back E.M.F. per phase.
t = number of turns per phase.
$\sim$ = frequency of supply.
k = a factor to compensate for distributed winding.

The only point in which the above formula differs from that for the transformer is in the introduction of the factor k. As it is impossible, and undesirable for other reasons, to concentrate the windings of an induction motor in one slot, it follows that they are not all acted upon by the flux at the same time, and the E.M.F. due to them when joined in series will consequently be slightly less than the sum of their separate E.M.F.s; hence the use of the factor k, which is similar to the K used in the formula for alternators. A good average value for k is ·95.

It is evident that before we can obtain the number of turns per phase from the above formula, we must know or assume the value of N, the stator flux. The flux N is equal to the product of B_g, the average flux density in the air gap, and A, the area of the air gap. To assume a value of B_g is, therefore, one way of getting a trial value for N. To determine whether the value of B_g chosen is a suitable one, it becomes necessary to work through a magnetic table, precisely as was done for the alternating and the continuous current machines previously analysed, and from this table to calculate the magnetising or exciting current of the motor. If the magnetising current thus found approximately corresponds with the value which we have previously determined to be necessary to enable the specification to be complied with, we are in a position to continue the design. Should the magnetising current as found from the table differ widely from that required, a new value of B_g must be assumed, and the number of turns, magnetic table, and magnetising current recalculated. In Fig. 541 is shown the path of the magnetic flux in a four-pole induction motor, from which it is evident that although the motor has no polar projections, the path followed by the flux is exactly the same as in the other types of machinery previously analysed. We will now proceed to the calculation of the number of the stator turns per phase, and in order to do this, will assume a value for B_g. As a rule, for motors which have no severe conditions as to overload capacity to fulfil, B_g varies from 20,000 to 25,000 lines per square inch, but in crane, lift, or traction motors, it may go as high as 35,000 lines per square inch. In this case, we will assume a B_g per sq. in. of 23,100. The next step is to calculate the area of the air gap, and thus obtain N. The most satisfactory way of doing this is to take as the gap area the average of the gross area of a stator pole face less the slot openings and

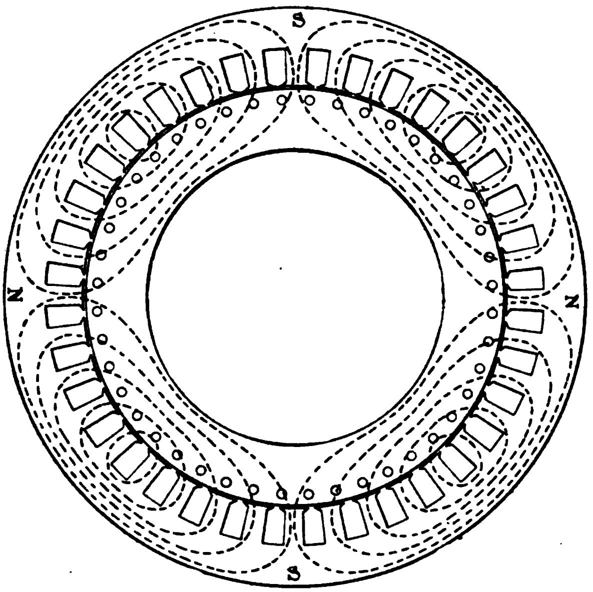


FIG. 541.—DIAGRAM OF THE FLUX IN A FOUR-POLE INDUCTION MOTOR.

the gross area of a rotor pole face less the slot openings.

In this case,

Gross length of core = 4·25 in.
Pole pitch at stator face = 5·3 in.
No. of stator slots per pole = 9
Stator slot opening = .0985 in.
Pole pitch at rotor face = 5·275
No. of rotor slots per pole = 12 approx.
Rotor slot opening = ·0394 in.

Thus, gross area of stator pole face

$$= 5{\cdot}3 \times 4{\cdot}25 = 22{\cdot}5 \text{ sq. in.}$$

Area of slot openings

$$= 9 \times {\cdot}0985 \times 4{\cdot}25 = \underline{3{\cdot}77} \text{ sq. in.}$$

$$\text{Area stator pole face} = \underline{18{\cdot}73} \text{ sq. in.}$$

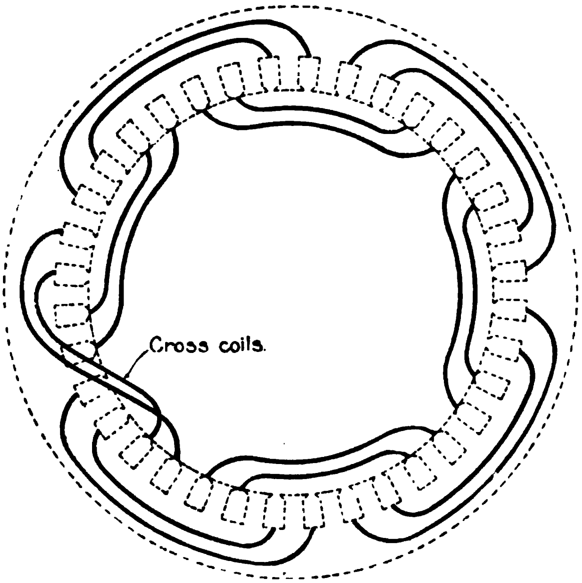


FIG. 542.—DIAGRAM SHOWING A CROSS-COIL WINDING.

And gross area of rotor pole face

$$= 5{\cdot}275 \times 4{\cdot}25 = 22{\cdot}4 \text{ sq. in.}$$

Area of slot openings

$$= 12 \times {\cdot}0394 \times 4.25 = \underline{2{\cdot}01} \text{ sq. in.}$$

$$\text{Area rotor pole face} = \underline{20{\cdot}39} \text{ sq. in.}$$

$$\text{Area of gap} = \frac{18{\cdot}73 + 20{\cdot}39}{2} = 19{\cdot}56 \text{ sq. in.}$$

The total flux is therefore $23{,}100 \times 19{\cdot}56 = {\cdot}4525 \times 10^6$. We can now substitute this value of N in the formula, and we then obtain the number of turns per phase. The E.M.F. used in this formula is the applied E.M.F. per phase less the voltage drop due to resistance, which we have already assumed to be 6·4 per cent. The formula then becomes

$$206 = \frac{4{\cdot}44 \times {\cdot}95 \times T \times {\cdot}4525 \times 10^6 \times 50}{10^8}$$

$$\therefore T = \frac{206 \times 10^8}{4{\cdot}44 \times 95 \times {\cdot}4525 \times 10^6 \times 50} = 216.$$

The turns per phase are 216, and the conductors per phase are therefore $216 \times 2 = 432$. It is essential that this number be a multiple of the number of slots per phase, as one must have a whole number of wires in one slot. In our case the slots per phase are 12, and we therefore have $\frac{432}{12} = 36$ wires per slot. If the number of conductors had not been a multiple of the number of slots the nearest multiple would have been taken and the value of B_g corrected. Before we can settle upon the size of the slot it will be necessary to decide upon the section of the wire. We know that the stator C^2R loss per phase is to be about 60 watts per phase, and the stator current is $5\propto$. The permissible resistance for the stator is therefore $\frac{60}{25} = 2{\cdot}4\ \omega$ per phase hot. The winding will be in two coils per phase and two ranges, exactly as if for a three-phase alternator. It is worth mentioning here that if the number of pairs of poles should be odd there will be a coil crossing from one range to the other, as shown in Fig. 542, which illustrates a six-pole winding, the number of pairs of poles here being an odd number, viz. three. This cross coil does not occur in our particular case, and from a simple scale sketch the length of a mean turn of the stator winding is found to be 32 ins. The total length of wire per phase upon the stator is therefore $\frac{32 \times 216}{12} = 577$ feet. We see from this that 577 feet of the wire must have a resistance of 2·4 ω when hot, say at 40° C. From a wire table we find that the diameter of a wire having this resistance is ·052 in. bare and ·062 in. when double cotton covered. A detailed account of the design of the slot cannot be given here, but suffice it to say that, allowing a suitable margin for slot insulation, the size and shape of the slot to contain the thirty-six wires is shown at *a* in Fig. 543. Most makers have standard sizes of slots, and it is generally a matter of fitting the wires into one of these standards.

The number of rotor bars is fixed by the number of slots which are to be used, as in a short-circuited or squirrel cage winding there is one bar per slot. In our case the number of bars will be forty-nine.

The current density in rotor bars varies from about 2,500 to 4,000 amperes per sq. in. In our case, taking as a trial value 3,700 ∝ per sq. in., the area of the bar will of course be given by the current per bar ÷ 3,700.

Now C_r, the current in the rotor bar, is given by

$$C_{sec} \times \frac{Z_s}{Z_r}$$

where C_{sec} = the full load secondary current as obtained from our preliminary Heyland diagram.

Z_s = the total number of stator conductors.

and Z_r = the total number of rotor conductors

In our case,

$$C_r = 4·4 \times \frac{432 \times 3}{49} = 116 \text{ amperes},$$

$$\text{Section} = \frac{116}{3{,}700} = ·0314 \text{ sq. in.}$$

This is given by a rotor bar ·2 in. in diameter.

The current in the end rings of a squirrel cage rotor is given by

$$C_{er} = \frac{Z_{pr}}{\pi} \times C_r$$

where C_{er} = current in the end rings.

C_r = „ per rotor bar.

Z_{pr} = rotor bars per pole.

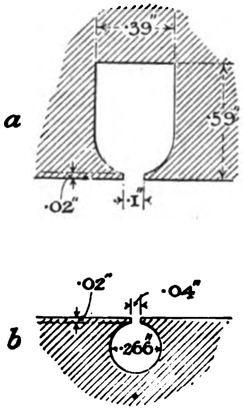


FIG. 543.—FULL-SIZE DIAGRAM OF STATOR AND ROTOR SLOTS.

In our case, this becomes

$$C_{er} = \frac{12·25}{\pi} \times 116$$

$$= 452 \text{ amperes.}$$

The current density in end rings is usually from 2,500 to 3,000 amperes per sq. in. For this particular case we will try 2,900 ∝ per sq. in. which gives us a section of $\frac{452}{2{,}900} = ·156$ sq. in. The total C^2R loss in the rotor is given by the formula

Total C^2R loss in rotor $= Z_r C_r^2 (R + ·2\ Z_{pr}^2 R_1)$

where Z_r = total rotor conductors

Z_{pr} = rotor conductors per pole

C_r = current in one rotor bar

R = resistance of one rotor bar

R_1 = resistance of the portion of an end ring which connects two adjacent conductors.

In our case this becomes

Total C^2R loss in rotor $= 49 \times 116^2 (·0001628 + ·2 \times 12·25^2 \times ·0001084)$ 179 watts.

Allowing 5 per cent. for resistance of

sweated joint between the rotor bars and end rings, the rotor copper loss becomes $179 \times 1{\cdot}05 = 188$ watts.

Having now decided the size of the stator and rotor slots, all that remains to be done before working out the preliminary magnetic table is to fix the depth of the stator and rotor cores. The average flux densities employed in stator cores vary from about 40,000 to 60,000 lines per sq. in. for 50 cycles per second, and in rotor cores, where the frequencies are very low, from 40,000 to 70,000. Let us take B sq. in. in the stator core as, say, 53,000. This will give a section of iron as $\frac{{\cdot}4525 \times 10}{2 \times 53{,}000} = 4{\cdot}270$ sq. in.

The gross length of the stator core is 4·25 in. and deducting 10 per cent. for insulation between the laminations, we obtain as the net iron length 3·825 in.

The depth of the stator core, behind the teeth is therefore $\frac{4{\cdot}27}{3{\cdot}825} = 1{\cdot}116$ in., say, $1\frac{1}{8}$ in.

Assuming B sq. in. in the rotor core to be, say, 44,500 and deducting 5 per cent. of the gross length for insulation between the thicker rotor plates, the depth of the rotor core behind the teeth is

$$\frac{\dfrac{{\cdot}4525 \times 10^6}{1{\cdot}0458}}{44{,}500 \times 4{\cdot}25 \times {\cdot}95} = 1{\cdot}2 \text{ in.}$$

The stator flux is here divided by the leakage coefficient, $1 + \sigma$, to get the rotor flux. The calculation of the areas and lengths in the magnetic table on page 595 cannot be gone into in detail here. Suffice it to say that the areas of stator teeth are taken half way up, and that of the rotor teeth one quarter of the slot depth from the rotor face, and that the maximum flux densities all through the motor are taken to correspond to, and to be produced by, the maximum values of the magnetising current. One word here with regard to the maximum values of B in the induction motor. It is found by calculation, and borne out by practical results, that the maximum value of B is not the average value multiplied by 1·575, as it would be if there were a pure sine distribution of the flux, but that $B_{max} = B_{average} \times 1{\cdot}7$. It is this factor, 1·7, which is used in the following calculations. Also, to be more nearly correct, we have assumed that half the magnetic leakage takes place in the stator, and half in the rotor, so that the flux in the air gap $= \frac{{\cdot}4525 \times 10^6}{1{\cdot}0229} = {\cdot}4420 \times 10^6$.

From the table we find that the number of ampere turns per pole to be provided by the maximum value of the magnetising current is 285. It can be shown that the magnetising effect of two or of three phases is twice that of one phase, so that the calculation of the magnetising current becomes simple. It is obvious that

$$C_{max} \times t \times 2 = \text{A.T.}$$

where

C_{max} = maximum value of magnetising current.
t = turns per phase per pole.
A.T. = ampere turns required per pole.
2 = constant, for the effect of the two or three phases.

In our case

$$C_{max} \times \frac{216}{4} \times 2 = 285,$$

whence $C_{max} = \frac{285 \times 4}{216 \times 2} = 2{\cdot}64$ amperes and virtual current $= 2{\cdot}64 \times {\cdot}707 = 1{\cdot}9$ amperes. This corresponds with our required value of 1·95 amperes as closely as is necessary.

If the magnetising current had differed much from the value 1·95 amperes, we should have had to assume a new value of B_g, higher or lower as the magnetising current was too low or too high, and worked through a new magnetic table.

To avoid the necessity of doing this, the writer has made use of a formula to give

TABLE OF MAGNETISING AMPERE TURNS.

PART.	N	AREA. SQ. IN.	B SQ. IN. AVERAGE.	B SQ. IN. MAXIMUM.	AMPERE TURNS PER IN.	LENGTH. IN.	AMPERE TURNS REQUIRED.
Gap . . .	$\cdot 4420 \times 10^6$	19·56	22,550	38,300	11,980	·0315	377
Stator teeth .	$\cdot 4525 \times 10^6$	11·85	38,200	64,900	7	1·14	8
Stator core .	$\cdot 27625 \times 10^6$	4·32	52,400	89,100	18	7·5	135
Rotor teeth .	$\cdot 4325 \times 10^6$	11·5	37,600	63,800	6	·512	3
Rotor core .	$\cdot 21625 \times 10^6$	4·875	44,400	75,500	10	4·7	47
Total ampere turns, per pair of poles, to be provided by the maximum value of the magnetising current							570

the value of B_g sq. in. when the magnetising current required has been determined from the preliminary diagram, and the area of the air gap is known.

The formula is—

$$B_g^2 = \frac{E_1 \times C_m \times M}{A \times \sim \times \delta \times p} \times 12 \cdot 5 \times 10^7.$$

where

E_1 = back E.M.F. per phase.
C_m = required magnetising current per phase.
A = area of air gap in sq. in.
δ = length of air gap per side, inches.
p = number of poles.
M = ratio of ampere turns for gap to total ampere turns required.

This ratio, M, varies from about ·5 for very highly saturated traction or lift motors to about ·9 for motors with long air gaps and low saturations.

Testing this formula for our case, we have—

$$B_g^2 = \frac{206 \times 1 \cdot 95 \times \cdot 662}{19 \cdot 56 \times 50 \times \cdot 01575 \times 4} \times 12 \cdot 5 \times 10^7$$
$$= 540 \times 10^6.$$

$\therefore B_g = 23{,}250$ lines per sq. in.

This would be about the density required to give us a magnetising current of 1·95 amperes.

All that now remains for us to do is to calculate the iron loss, see if the motor is all right as regards heating, and to construct the final Heyland diagram for the motor. The calculation of the iron loss is attended with some difficulty, as owing to the burring of the plates forming the core by filing and machining, and to the various stray losses which take place in end covers, the total iron losses are several times as great as would be found if the ordinary transformer iron loss curves were taken as a basis of calculation. Fig. 544 shows a curve from which the core loss can be approximately calculated. Vertically is plotted the product of the flux density in lines per sq. in. and the frequency in cycles per second divided by 10^5. Horizontally is plotted the stator core loss in watts per pound. On account of the low frequencies obtaining in rotors, due to the low value of the "slip," the iron loss in them is very small. To be on the safe side, however, it is a good plan to increase the core loss as calculated above by ten per cent. to allow for the rotor iron loss.

In our case the weight of stator iron is 42·5 lbs.

$$\frac{\text{B sq. in.} \times \sim}{10^5} = \frac{52{,}400 \times 50}{10^5} = 26 \cdot 2.$$

From the curve this is seen to correspond to a loss of 3·06 watts per pound, giving a stator iron loss of 3·06 × 42·5 = 130 watts.

Adding ten per cent. for rotor iron loss we have as the total iron loss = 143 watts. The friction and windage loss varies from less than 1 per cent. of the input in large motors to about 2 per cent. in small motors.

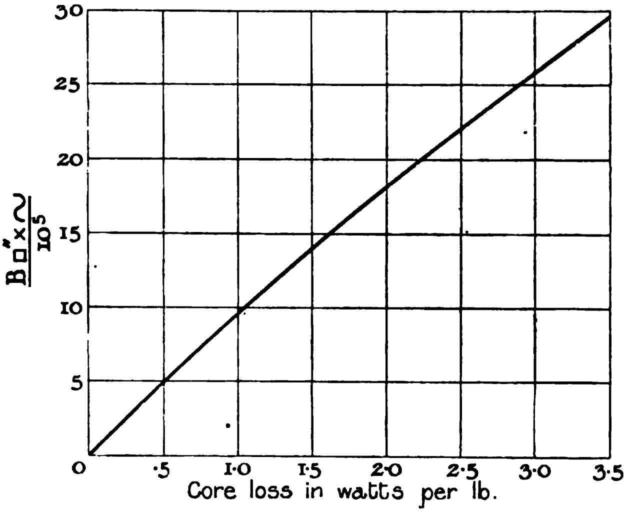


FIG. 544.—CORE LOSS CURVE.

Assuming 2 per cent. in our case, we obtain—

$$\frac{3 \times 746}{\cdot 8} \times \frac{2}{100} = 56 \text{ watts.}$$

The total no-load losses are therefore made up as follows:—

Stator and rotor iron losses = 143 watts.
Friction and windage . = 56 „
No load C^2R loss = $1{\cdot}9^2 \times 2{\cdot}38$ × 3 approximate . = 25·8 „
Total no-load loss = 224·8 „

The losses at full load are distributed as follows:

Stator and rotor iron losses	143	watts.
Friction and windage .	56	„
Stator C^2R loss . . .	180	„
Rotor C^2R loss . . .	188	„
Total full load loss .	567	„

Output = 3 × 746 = 2,238
Input . . . = 2,805
Efficiency . = 79·75 per cent.

Taking the ends and internal and external peripheral surfaces of the stator core the total area is 307 sq. in. The watts wasted in the stator at full-load are 130 + 180 = 310 watts.

Thus the watts lost per sq. in. are

$$\frac{310}{307} = 1{\cdot}01.$$

As a general rule, a loss of ·8 watts per sq. in. gives a temperature rise in the stator of about 60° F. above the surrounding air after a six-hour run. The temperature rise of this motor on the stator would probably be about 75° F. after a six-hour run. The rotor, having few losses in it, and rotating at a high speed will have quite a low temperature rise, and need not be considered here. A drawing showing the general arrangement of the various parts of the motor is given in Fig. 545. The one thing that remains to be done is to draw a complete Heyland diagram for the motor, and to plot from the diagram the test curves. This can be done by proceeding on the lines before indicated, but space does not permit of details being given here. When testing large motors in works where there are no facilities for making actual brake tests, the diagram can be constructed and test curves plotted without running the motor on load at all. The data required are the no-load current, watts and power factor, the short circuit current, watts and power factor when the rotor is clamped, and the rotor and stator resistances. It is advisable to

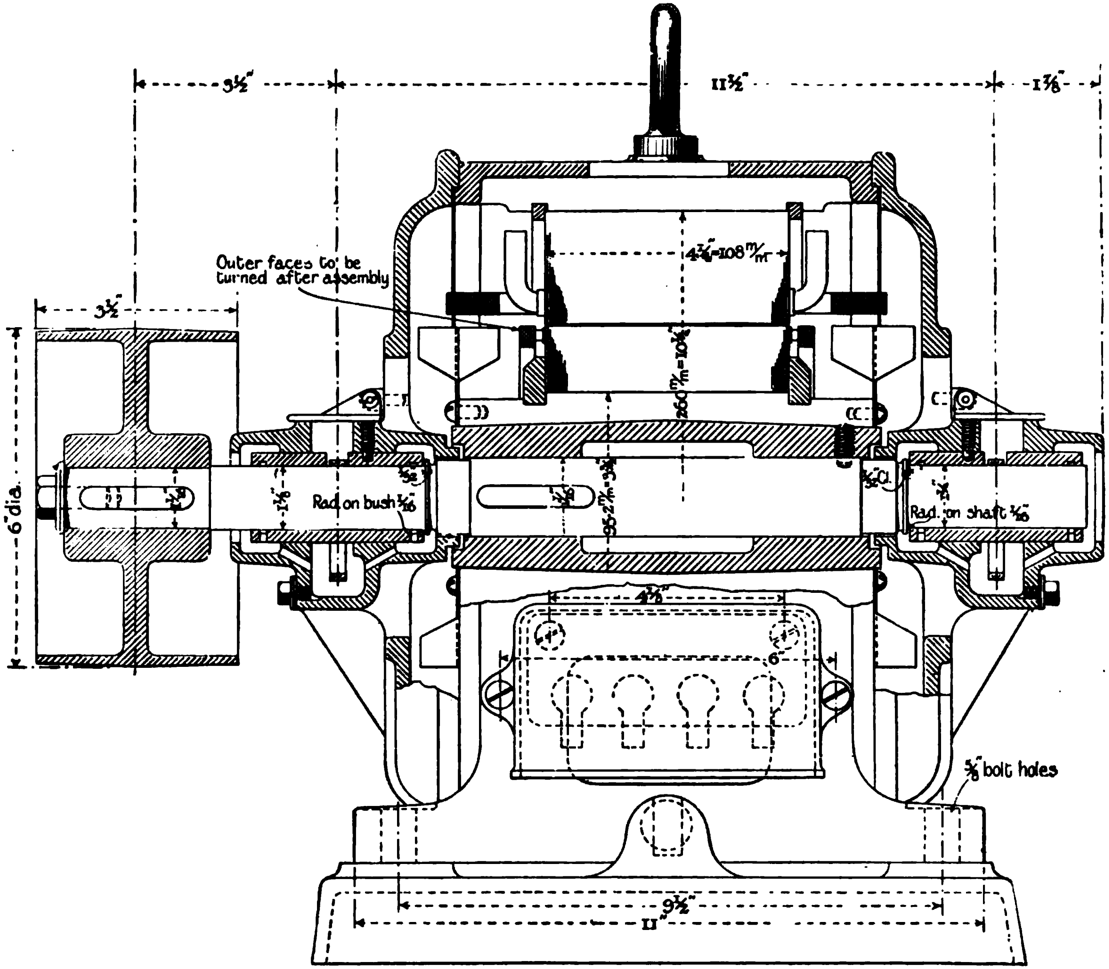


FIG. 545.—GENERAL ARRANGEMENT OF COMPLETE MOTOR.

take the short-circuit current with a reduced voltage, say half or one-third of the normal and correct the current obtained to normal voltage by simple proportion. A little consideration will show how the diagram can be constructed from the above data, and the test curves are plotted by taking a number of points on the outer circle, and scaling off the input torque, horse power, and slip corresponding to them. The power factor and efficiency are also easily calculated from these figures, and by plotting against brake horse-power, the required test curves are obtained.

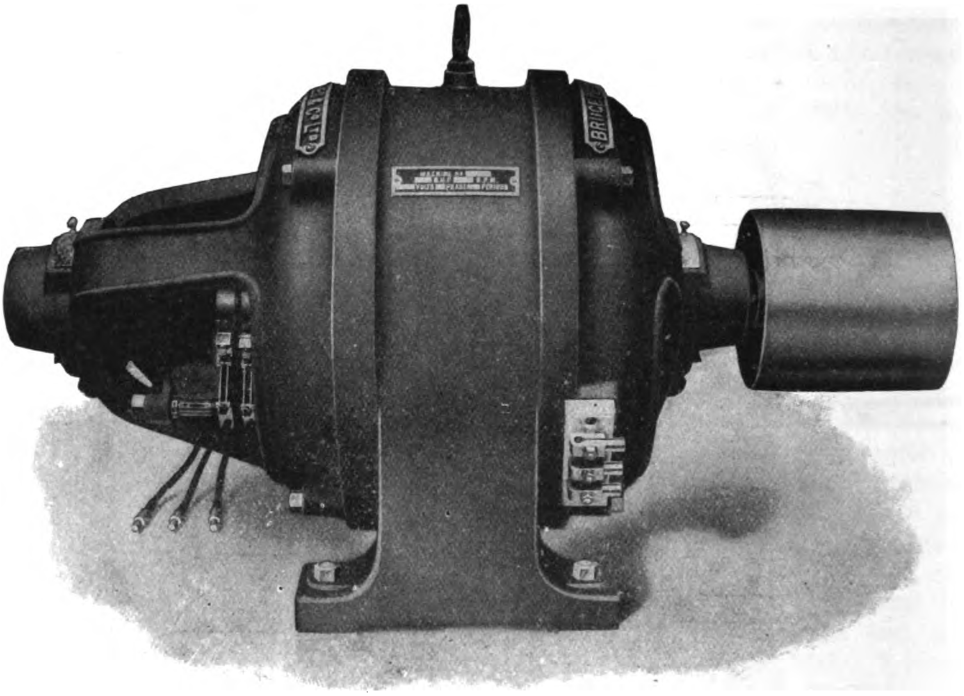


FIG. 546.—MESSRS. BRUCE PEEBLES' INTERNAL SLIP-RING MOTOR.

EXAMPLES OF INDUCTION MOTORS.

Messrs. Bruce Peebles and Co., Limited, make two- and three-phase induction motors in standard sizes, up to 150 horse-power, in the standard frequencies of 25 ∿ and 50 ∿, with both squirrel cage and wound rotors, and have standard voltages up to 500 volts, though of course machines may be built for much higher voltages.

The standard temperature rating of these motors is a rise of 80° F. (44·5° C.) after a six hour run, but with the addition of iron grids over the openings of the standard motors, the temperature rise will be increased to 90° F. (50° C.).

For starting up the squirrel cage motors an auto-transformer (*see* Section VIII.), is used, which is, as we have mentioned the usual device with such motors.

In Fig. 546 is shown the standard self-contained slip-ring motor, and Fig. 547 illustrates the equivalent standard motor with squirrel cage rotor, the motor being more compact in this case owing to the absence of the slip rings, which in this firm's slip-ring motors are carried inside the bearing and are not placed outside, as is very usual practice. This construction with internal slip rings renders unnecessary a hollow shaft through which to bring the slip-ring cables, which is of course always necessary in motors with outside rings (*see* Plate XI.); but on the other hand it does not permit of the employment of the same end plate for both slip-ring and short-circuited rotors.

The stator construction and winding was well shown by Figs. 533 and 534. The stator slots are nearly closed, the slots being as usual stamped in a completely closed condition, and then having a slit cut in them after the stator has been assembled and bored. The windings are of the usual hand-wound variety, the end bends being taped after the winding is complete. The slots are lined before winding with presspahn or mica troughs, the completed winding being dried in an oven for thirty-six hours, then varnished and baked again several times, the last coat of varnish being allowed to dry in the air. The wound stator core which we illustrate is for a 50 horse-power, 440 volt three-phase motor, 50 cycles, and 500 revolutions per minute, and there are therefore twelve poles.

Hand windings are used upon the rotors of these machines, and in Fig. 537 has been shown the completed rotor, as manufactured by this firm, with slip rings complete, this being a wire-winding in which the end-windings are prevented from flying out owing to the centrifugal force when running by means of iron hooks, round which the ends of the turns are passed. A similar rotor, by this firm but with a bar winding, has been shown in

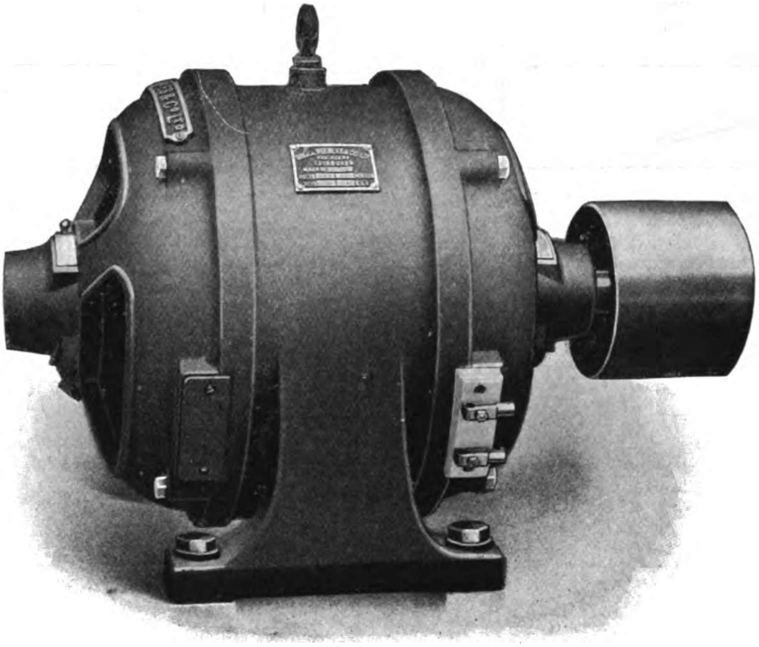


FIG. 547.—INDUCTION MOTOR HAVING SQUIRREL CAGE ROTOR.

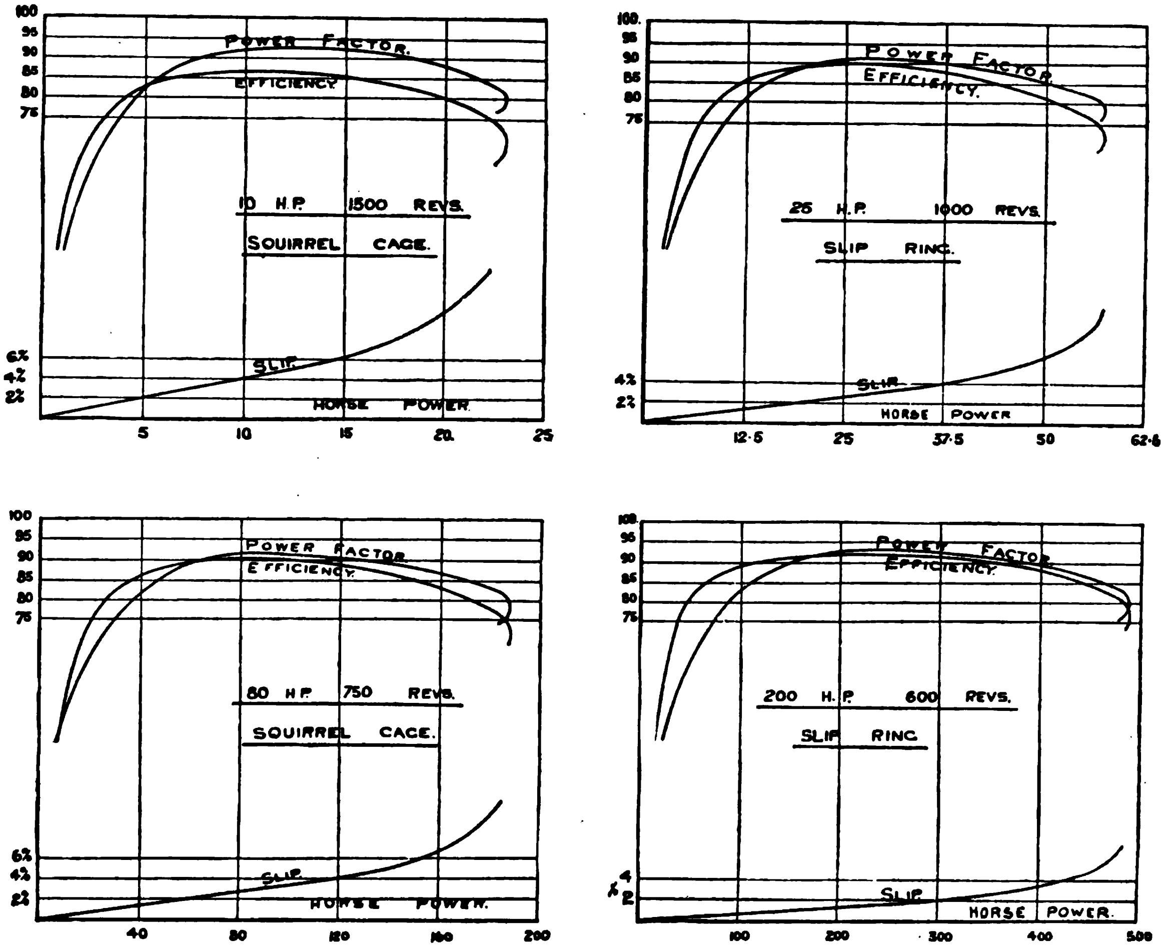
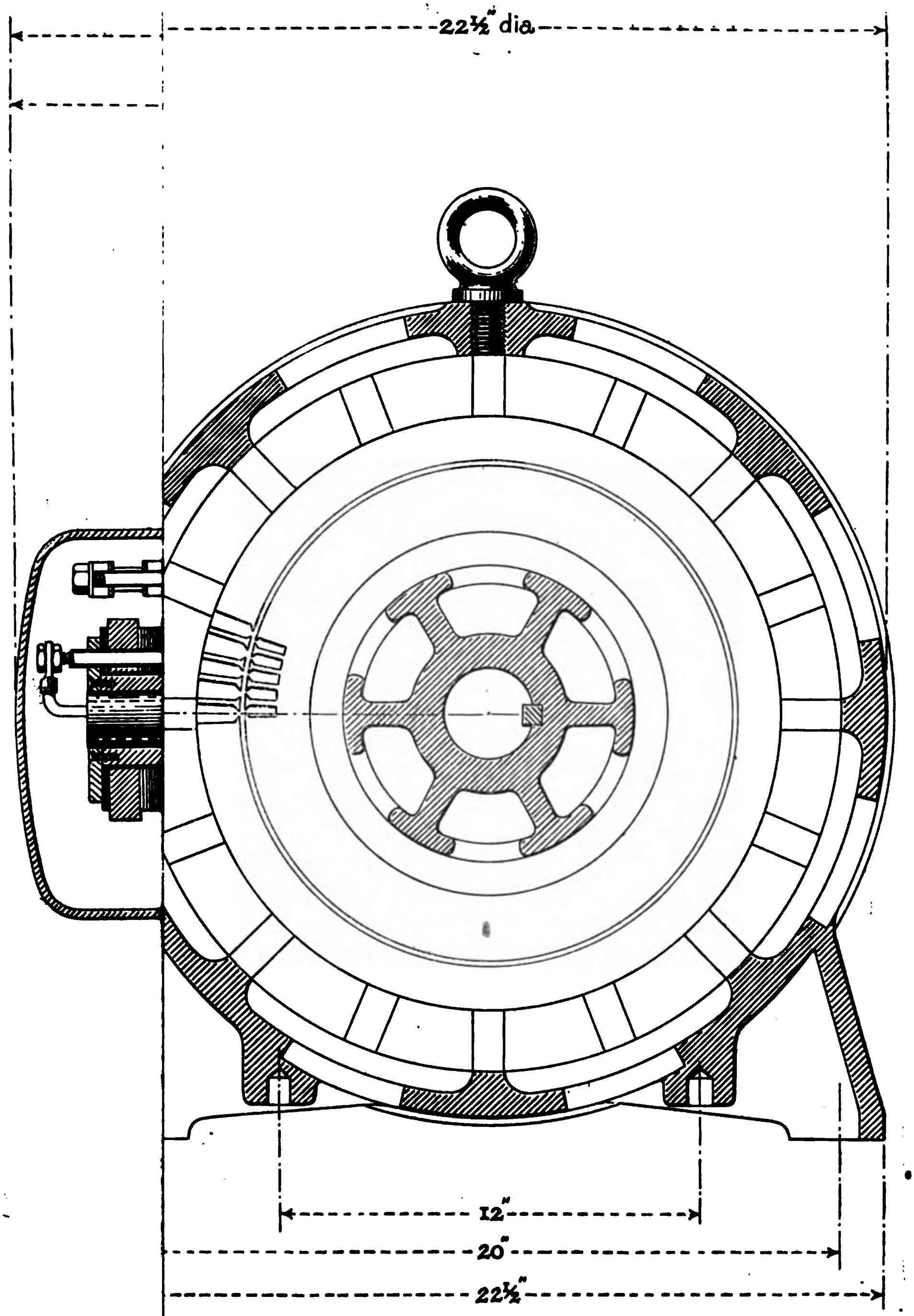


FIG. 548.—PERFORMANCE CURVES OF VARIOUS INDUCTION MOTORS (BRUCE PEEBLES AND CO.).



(LANCASHIRE DYNAMO AND MOTOR COMPANY) *(See page 601.)*

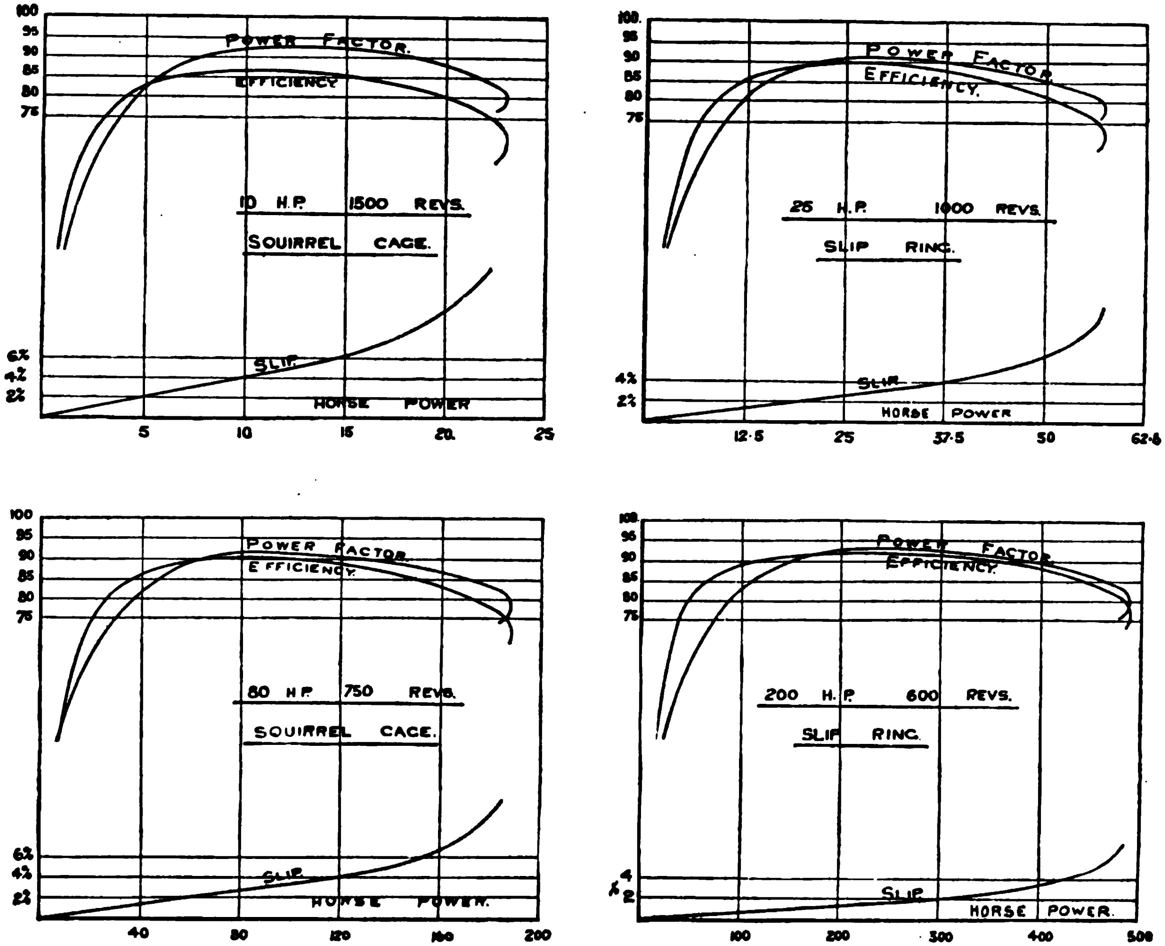
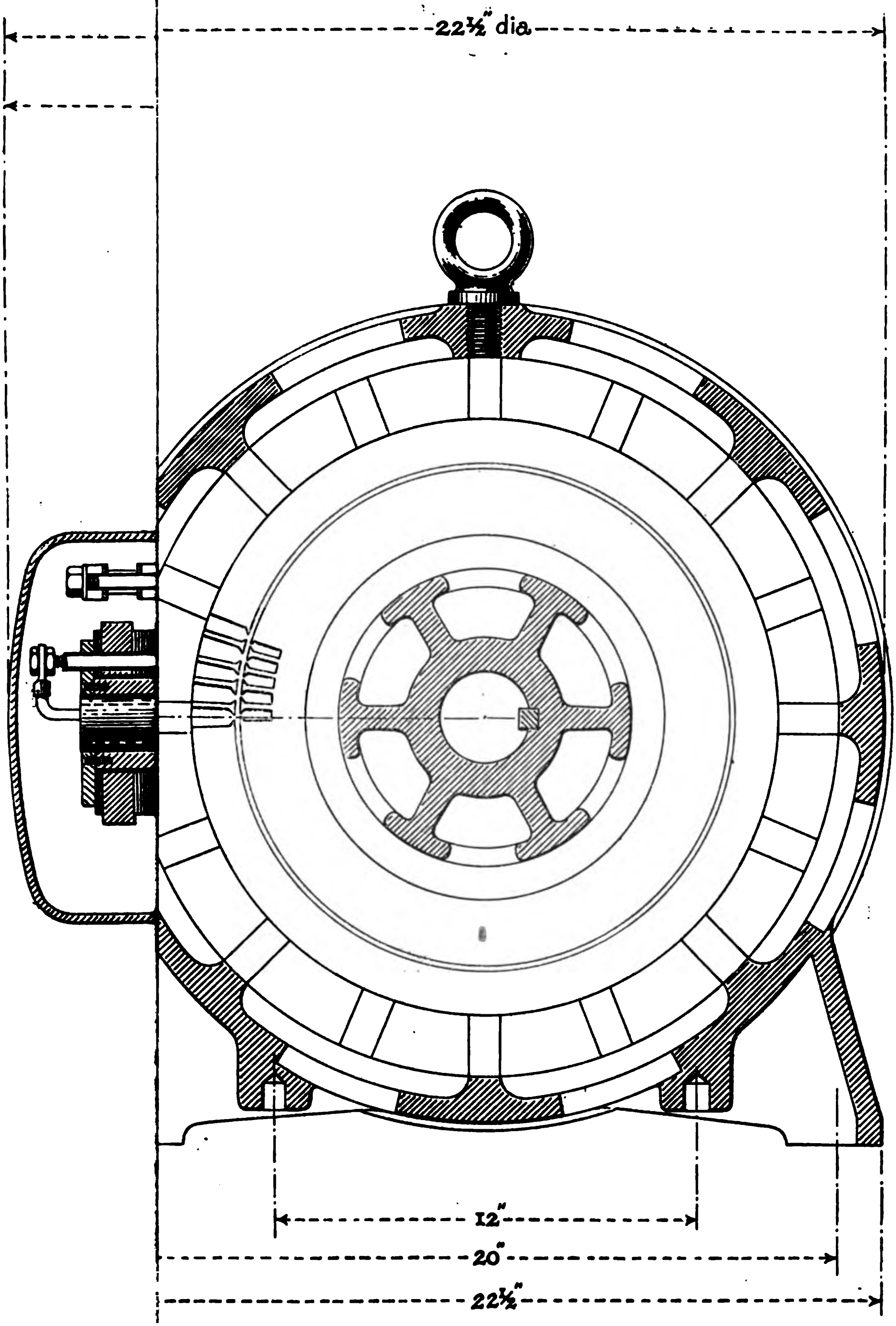


FIG. 548.—PERFORMANCE CURVES OF VARIOUS INDUCTION MOTORS (BRUCE PEEBLES AND CO.).



(LANCASHIRE DYNAMO AND MOTOR COMPANY) *(See page 601.)*

Fig. 538. The bar winding would be used in those cases where the size of the conductors, owing to the heavy current necessary, does not permit of the use of round wires, which, of course, become unwieldy after a certain size is exceeded.

A squirrel cage rotor by this firm was also shown in Fig. 536, and it will be noticed that the end plates have a flanged rim carried out beyond the massive short-circuiting ring which, in addition to providing mechanical support, affords some protection against injury and accidental contact with the short-circuiting ring.

In Fig. 548 we show representative performance curves of Messrs. Peebles' motors. The most interesting point to notice is the good power factor of the 10 horse-power squirrel cage motor. As we have pointed out, the running performance of this type of motor is excellent, and it is always possible to obtain a slightly better power factor with it than with the wound rotor.

It should also be noted that with higher powers the efficiency goes up while the slip goes down.

A sectional drawing of a three-phase 75 horse-power induction motor for 50 ∿ at 480 revolutions per minute, with external slip rings, by the Lancashire Dynamo and Motor Company, Limited, is shown in Plate XI.

The slip rings are entirely enclosed in a circular box of cast-iron to afford complete protection. The stator case has cored apertures to provide adequate ventilation, and the rotor core is well ventilated, being built up on a cast-iron spider with six arms. The ample length of the bearings should be noticed, for in induction motors, the air-gaps being always very short, it is very necessary to provide ample bearing surface to ensure the minimum amount of wear, and thus preserve as far as possible accurate alignment of the bearings. Each bearing is provided with two oil rings dipping into the usual oil wells. A bar winding is used on the rotor.

A good feature of the motor is that the cables running through the hollow shaft are brought out right to the end of the shaft and connected, by means of sweating thimbles and connecting straps, to the slip rings. This is a better arrangement than taking the cables through apertures near the end of the shaft to the slip rings, as if anything shakes loose with such concealed connections, it is often very difficult to set the matter right, but by bringing the cables out right to the end of the shaft, all such possible inconvenience is avoided. Fig. 549 shows the actual motor with the slip ring cover removed. Carbon brushes are used on the slip rings, the brush holders being of horseshoe form, four carbon brushes pressing on each ring. Carbon brushes are now being used extensively for induction motor slip rings, and their chief advantage is that there is much less wear on the rings and less attention is needed than with copper brushes, but otherwise the copper brush is quite satisfactory and there is no trouble with heating. Of course the loss at the slip rings with carbon brushes is very much greater (generally about ten times the loss takes place) than with copper brushes; but if the current per phase in the rotor is not excessive, carbon brushes are certainly preferable. On the other hand, with large motors where the rotor currents may run to hundreds of amperes, copper gauze brushes are the standard practice, but in such large motors brush-lifting and short-circuiting devices are usually employed, so that it is only at starting that the brushes are bearing on the slip rings. In this case, the wear due to the copper brushes is unimportant, and if carbon brushes were employed the brush gear would have to be much more massive and the bearing surface of the brushes much greater, so that with the brush-lifting device no particular

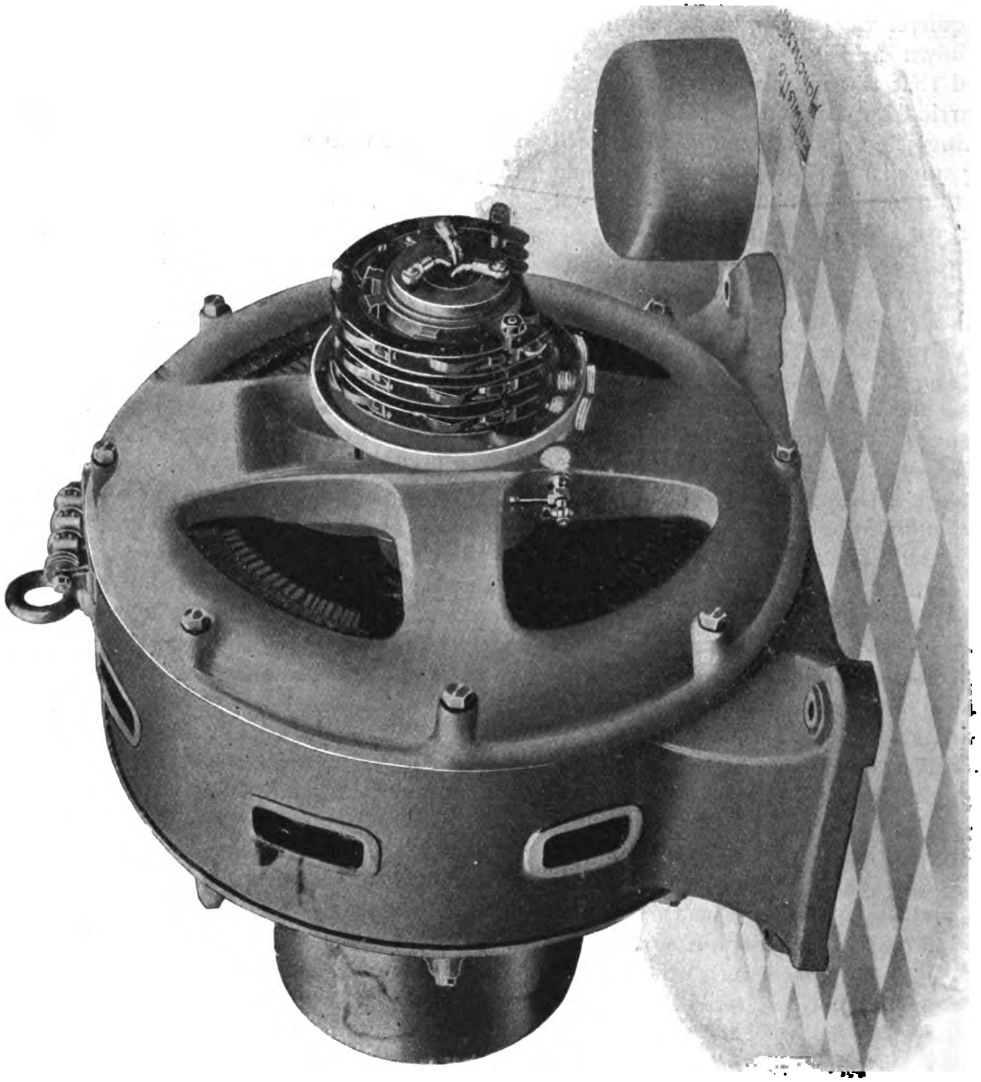


FIG. 549.—INDUCTION MOTOR. VIEW SHOWING HOLLOW SHAFT AND SLIP RINGS.

advantages would result from the use of carbon brushes.

An example of the standard induction motors made by Messrs. Siemens Brothers' Dynamo Works, Limited, is shown in Fig. 550.

These motors have elaborately ventilated cases and are made with either internal or external slip rings.

The motors can be wound for the usual frequencies and pressures, but the firm build standard machines for certain voltages up to 500 volts at the standard frequency of 50 ∼.

The light load currents vary from one-fifth of normal current for large motors up to one-third of normal current for small motors. As the no-load current of an induction motor always has a very low power factor (varying, say, from ·15 to ·30), the power taken at no load is, of course, much less than would be given by the product of the terminal volts and input in amperes running light. The overload capacity of the motors is not less than 100 per cent. above the normal torque for three-phase motors and 75 per cent. for two-phase motors, and as the torque in an induction motor drops roughly in proportion to the square of the terminal E.M.F., it follows that the voltage may drop about 30 per cent. before the motors will pull up at normal full-load torque.

Messrs. Siemens use for squirrel cage motors a star-delta switch, that is, at starting the stator winding is connected up in the mesh or delta (Δ) fashion, giving for starting a much higher magnetic density in the motor (neglecting the effect of the saturation of the iron, $\sqrt{3}$ or 1·73 times the normal magnetic flux), which gives the motor a much higher starting torque for a given current. When the motor is started the connection is changed over to the usual star connection by means of the special inter-connecting switch. The makers give the following figures for the starting torque and current for their squirrel cage motors, using the special star-delta switch:—

B.H.P.	TORQUE.	RUSH OF CURRENT.
Up to 10	40 % normal	1·4 times normal
10 „ 30	33⅓% „	1·5 „ „
30 „ 100	27 % „	1·6 „ „

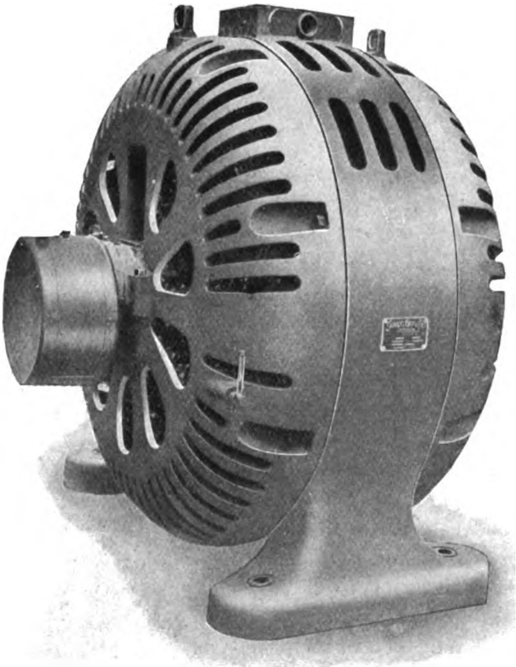


FIG. 550.—INDUCTION MOTOR HAVING SPECIALLY VENTILATED CASING.

With wound rotors, with suitable resistance in circuit, as we have already mentioned, any well-designed induction motor will give practically full load torque for full load current, and from the above comparison it will be seen how inferior are the starting conditions of the squirrel cage rotor, even with the special starting arrangement of the star-delta switch. The results as regards starting torque and current with the star-delta switch should

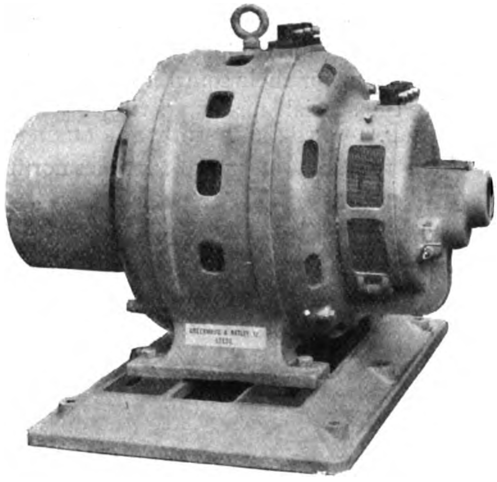


FIG. 551.—"VENTILATED" TYPE OF INDUCTION MOTOR.

be compared with similar data we give in Chap 3, Section VIII., relating to the use of auto-transformers with American motors.

The makers state that the method of starting up with auto-transformers gives results generally inferior to the above figures.

The starting torque of squirrel cage rotor machines can be considerably improved as compared with the above figures, and the makers claim that if efficiency is sacrificed to some extent, 50 per cent. better results can be obtained than the figures quoted.

Fig. 551 shows a three-phase induction motor by Messrs. Greenwood and Batley, Limited, with well-ventilated case and internal slip rings, all openings to any live part of the motor being protected with coarse mesh gauze coverings.

The terminals for both the stator and rotor windings are protected with insulating caps, the only live metal exposed being the ends of the sweating thimbles, and when connected to the supply cables these could be taped over, and thus the motor would expose no live metal whatever.

The cast iron webs which give strength and rigidity to the bearing in the end plate of this motor as well as the neat design of the stator frame and end plates are also worthy of note.

A completely enclosed three-phase motor by Brown, Boveri and Co., is shown in Fig. 552. The motor is of 20 horse-power and works on a supply at 500 volts and 50 ∿, it has a speed of 1,000 revolutions per minute; it will be noticed that the starting

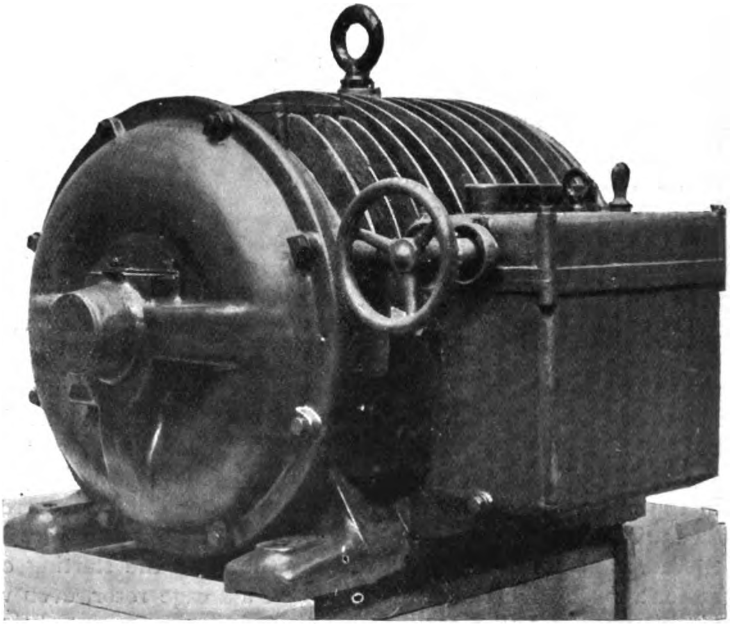


FIG. 552.—TOTALLY ENCLOSED TYPE OF INDUCTION MOTOR WITH ENCLOSED STARTING SWITCH.

resistances and switch gear are all enclosed in gas and water-tight casings, and that the motor is therefore suitable for working in damp positions or in places where an open type motor would create a risk of fire. Since the conductors in the motor cannot be cooled by allowing air to come into direct contact with them the heat generated in them must be *conducted* away through the stator casing which is provided with the radiating ribs shown to enable it the more readily to dissipate this heat.

Another three-phase motor by the same firm is shown in Fig. 553, which it will be seen is of the open type and has its rotor core plates carried upon a cast iron spider. This rotor is of the wound type, the ends of its windings being connected to three slip rings which can be seen just behind the near bearing; one of the connections from the rotor winding can also be seen securely clamped to an arm of the spider. The motor is of 300 horse-power, and runs at 300 revolutions per minute upon a supply at 500 volts and 50 ∿.

The handle seen protruding from the end plate casting is for short-circuiting the slip rings on the rotor and lifting the brushes after the motor has run up to speed. The motor is provided with a machined bed-plate, along which the stator may be slid when necessary.

Fig. 554 shows an 85 horse-power three-phase motor which runs at 428 revolutions per minute on a supply at 500 to 450 volts and 50 ∿. It will be seen that the starter is built on to the housing, and is contained in a closed iron case

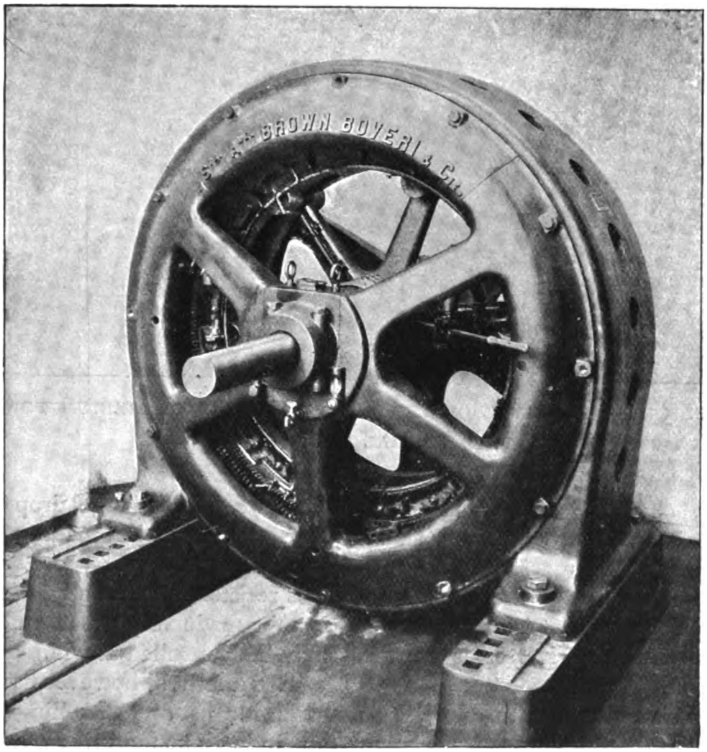


FIG. 553.—OPEN TYPE OF THREE-PHASE MOTOR FOR LARGE POWERS.

having ribs cast upon it to enlarge its cooling surface.

The rotor is of the wound type, and the slip rings and brushes of the motor may be seen, as may also a short-circuiting device connected to a chain wheel on the near end of the starter. The switch connecting the motor to the supply is placed underneath the starter and coupled by means of a chain to the chain wheel shown, and consequently to the short-circuiting device ; this arrangement ensures that the slip rings are not short-circuited when the current is first switched on, and also that the starter is in the correct position.

Another interesting feature of this motor is the ventilating fan blades seen in the interior of the rotor, by which air is forced through the ventilating ducts provided in the rotor and stator.

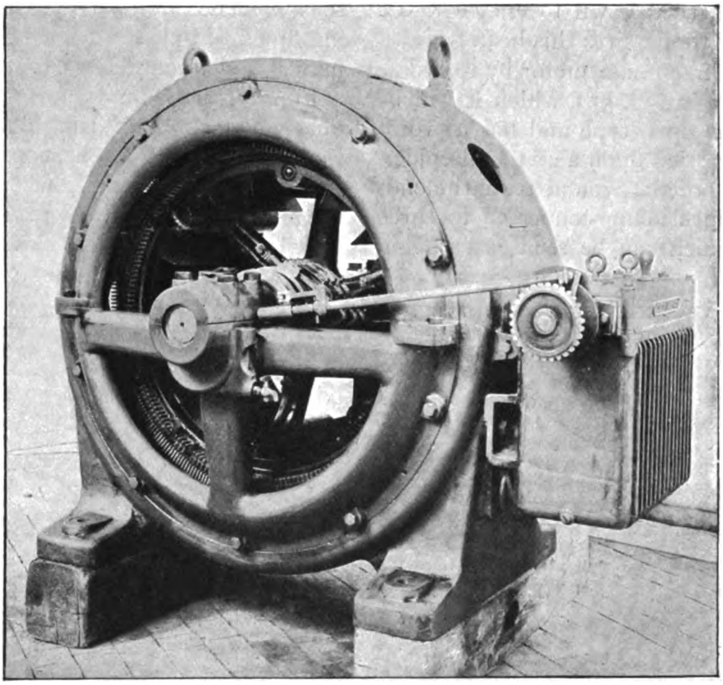


FIG. 554.—OPEN TYPE OF THREE-PHASE MOTOR FOR MEDIUM POWERS, WITH SPECIAL STARTING GEAR.

SPEED VARIATION OF INDUCTION MOTORS.

By resistances in rotor circuit.—The induction motor under load "slips" below the synchronous speed by an amount depending upon the resistance of the rotor winding. The slip is practically proportional to the voltage drop in the rotor, and, therefore, by making the rotor of very high resistance, or by introducing this resistance externally, the voltage drop can be made very great, and thus the slip may be controlled at will.

This method, however, is very wasteful as a means of controlling the speed of an induction motor, as a reduction of the motor speed to half of the normal, for instance, necessitates a loss of 50 per cent. of the input in the rotor resistance, thus being not only very wasteful of energy, but entailing large and expensive controlling resistances. It is resorted to in special cases, but on account of its obvious disadvantages, only very rarely.

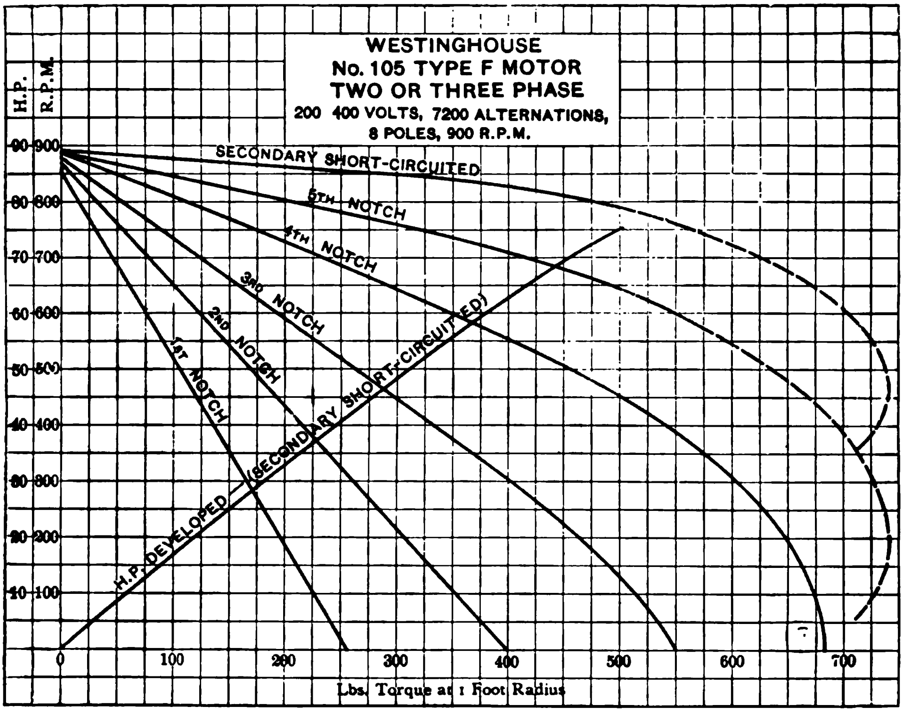


FIG. 555.—CURVES CONNECTING TORQUE AND SPEED FOR AN INDUCTION MOTOR, WITH VARIOUS ROTOR RESISTANCES INSERTED.

The performance curves of a Westinghouse two- or three-phase motor at 200 or 400 volts and 7,200 alternations per minute (60 ∿ per second) is shown in Fig. 555. This motor has a wound rotor arranged for the insertion of external starting and regulating resistance.

The torque in pounds at one foot radius is plotted against horse-power and revolutions per minute as ordinates. A torque curve is plotted for each contact or "notch" on the rotor resistance, and these curves give a good idea of the effect of varying the resistance in the rotor. When running on the first notch with all the resistance in circuit, the slip of the motor is very great with increase of load, but the maximum torque attained, *i.e.* when the speed has dropped to standstill (with 100 per cent. slip), is much lower than the torque which can be exerted with less resistance in the controller.

By resistances in stator circuit.—Resistances may also be inserted in the stator winding and a certain speed variation obtained, but the torque of the motor falls very rapidly as the terminal voltage is reduced, for the torque of an induction motor is reduced approximately as the square of the applied voltage, and as the maximum torque of the ordinary 50 ∿ motor is rarely more than two to two and a half times the normal at full voltage, it will be seen that any considerable fall in the voltage at the terminals will soon cut the torque down to an amount which cannot be permitted if the motor is to carry an overload. Moreover, the speed variation which can be obtained by a reduction in the stator voltage is in any case small.

By changing the number of poles.—Speed variation of an induction motor can also be obtained by the obvious device of changing the number of poles by altering the connections of the stator coils while the motor is running. This method seems attractive theoretically, but practically it necessitates clumsy switchgear. It is easily seen that if we change the effective number of turns per phase in the stator winding we shall increase or diminish the flux per pole of the motor and thus alter its whole performance, causing a great diminution of the torque with increase in the number of effective turns per phase. By reducing the turns we get into other troubles, such as overheating of the iron due to the high flux densities and a very heavy magnetising current.

This device has only been resorted to in a few special instances, and it is seldom to be recommended.

By "tandem control."—This method is only applicable where two motors of the slip-ring type are being employed, as for instance, in traction work, and is analogous to the series parallel control of the direct-current series motor. In one method the supply voltage is applied to the stator windings of one motor, the rotor of which supplies current to the stator windings of the other, and starting resistances are inserted in the rotor windings of this second motor ; when the motors are required to run on the top speed the supply voltage is applied direct to the stators of each motor. In a more recent method the rotor windings of the two motors are placed in series, the stator windings of the one being connected to the supply and of the other short-circuited. In this case the rotor windings of the second motor act as starting resistances for the first, and also induce currents in the stator windings of the second, motor. This method has the advantage that the two motors may be similar, and it is not necessary as in the first case to wind the rotor of the first motor to give a high voltage (for the stator of the second).

The reversal of polyphase motors is effected very easily by reversing *one phase* of the stator winding.

This is fairly obvious, but can readily be confirmed by the reader for himself by re-drawing the diagram on page 396 or page 571 and giving one of the fields a reversed sense. This will be seen to give the resultant field a reversed rotation.

SINGLE-PHASE MOTORS.

We have already mentioned in Chapter IV. that certain types of single-phase motors have achieved practical success, and that the newest types have already been adopted in some cases for heavy traction work.

We may divide single-phase motors into two primary classes :—

I. The single-phase induction motor.

II. The commutator motor.

The principles under which the induction type of single-phase motor operates are explained in Chap. VIII. of this section, dealing with motor principles in general. At this point, it will suffice to mention that the induction type is not self-starting and that to start such a motor without having recourse to purely mechanical means, we must make it at starting imitate the action of a *polyphase motor* by the device of "phase splitting," dividing the single-phase supply into two branches and producing a phase-difference between the two as mentioned in Chapter IV.

Condensers were some years ago employed for the purpose of giving a leading current to assist starting, but owing to the costliness and unreliability of condensers generally their use has not extended, and in those "split-phase" motors which have achieved a fair success, the device of an auxiliary starting coil wound between the running stator winding, in conjunction with or without the use of choking coils in the starting switch, has been generally adopted.

Some examples of these "split-phase" motors which have been quite extensively used during the last ten years or so are described below.

The first is the Langdon-Davies motor, the wound stator of which is shown in Fig. 556.

This is a two-pole motor manufactured by the Langdon-Davies Motor Company, Limited, of London. The motor has three terminals, two only being used, connected to the single-phase supply when the motor has once started up, while the third terminal is connected to the starting coil, the other end of the starting coil being connected to one of the running terminals.

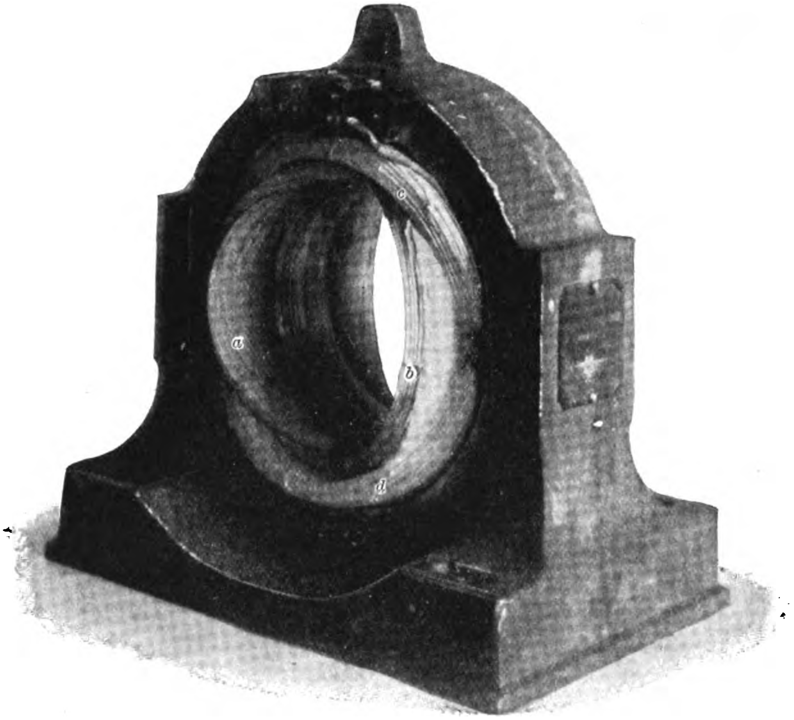


FIG. 556.—STATOR OF LANGDON-DAVIES SINGLE-PHASE INDUCTION MOTOR.

The stator is wound with four coils, *a*, *b*, *c* and *d*, two of which are the "running coils" and the other two "starting" coils. The inner coils, *a* and *b*, are the "running" coils, while the two outer coils, *c* and *d*, wound in the horizontal plane of the motor are the "starting" coils. The "starting" coils are an auxiliary winding wound in the same slots as the running coils, but the magnetic flux produced by these coils is at right angles in space to that produced by the "running" coils, which are wound in the vertical plane of the motor.

At starting currents flow through the two sets of coils in parallel. The necessary phase displacement between the two fluxes is produced by the two coils being of dif-

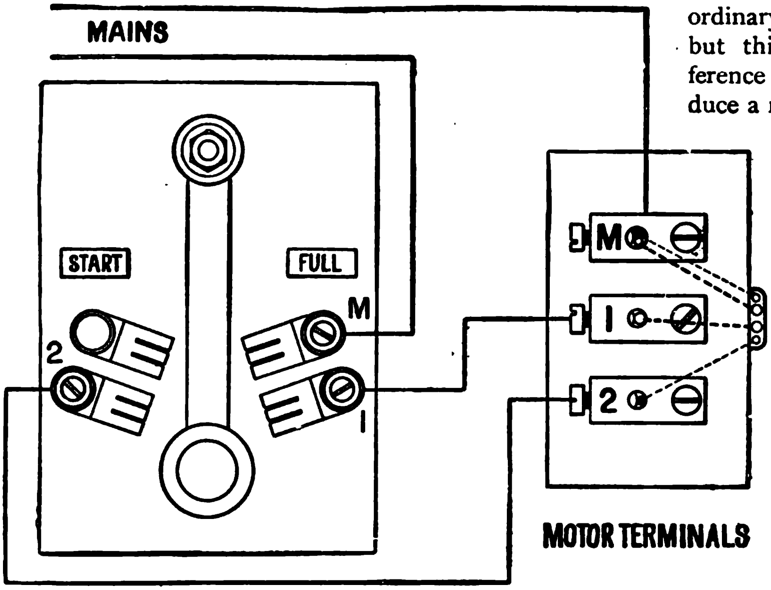


FIG. 557.—STARTING CONNECTIONS OF LANGDON-DAVIES MOTOR.

ferent length and, consequently, of different self-induction, while an external resistance is inserted in the running coils at starting in order to balance the current in the two coils, this resistance being cut out when the motor has run up to speed. The phase difference produced is only small, about one-eighth of the period as against the displacement of a quarter-period between two single-phase currents in quadrature (the ordinary two-phase system); but this small phase difference is sufficient to produce a rotating field which, though not by any means a perfect one, yet is sufficient to start up the motor light. These motors at starting give about a quarter full torque with full load current, and are often supplied with a loose pulley.

A diagram of the starting switch is shown in Fig. 557, where M, 1 and 2 are the motor terminals. The motor terminal, M, seen on the right, has both running and starting windings connected to it, and is connected directly on to the supply, while terminals 1 and 2 are the other ends of the running and starting coils respectively; the other main is connected to the terminal marked M on the starting switch, and also by a connection which is not shown, to the

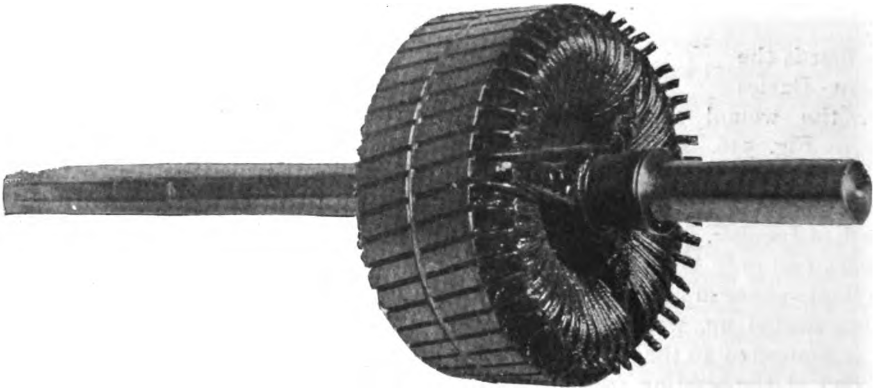


FIG. 558.—LANGDON-DAVIES SHORT-CIRCUITED ROTOR.

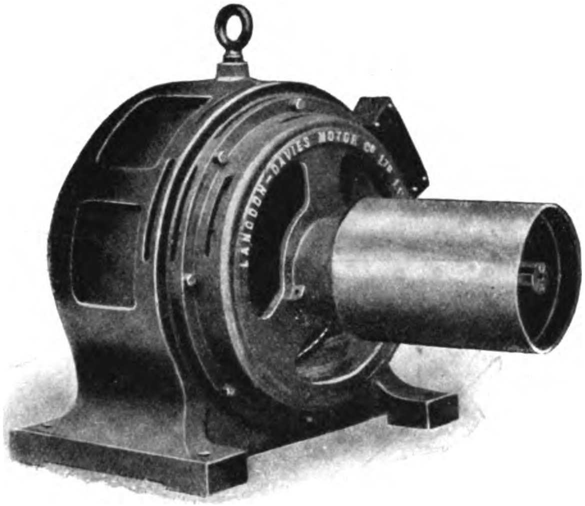


FIG. 559.—LANGDON-DAVIES SINGLE-PHASE INDUCTION MOTOR.

switch handle. The resistance to be inserted in the main circuit is stretched between porcelain insulators behind the starting switch, and is connected between the terminals marked 1 and that immediately below the word "start." At starting, the handle is put over to the side marked "start," in which position single-phase current is supplied directly from the switch handle to the starting coils 2, and to the running coils through the external resistance. The motor is allowed to run up to speed, and then the switch is brought over to the side marked "full," when current is supplied direct to the running coils only (through the switch handle from terminal M to 1), and the circuits of the starting coils and resistance are broken.

The rotor of this motor is shown in Fig. 558. The slots are very narrow, and are arranged obliquely to the centre line of the shaft, this arrangement ensuring better running by minimising any possible "cogging" effect between the rotor and stator teeth, which must be carefully guarded against. There are thirty-two slots in the stator, and forty-seven slots in the rotor, the ratio between these two being an incommensurable number, and this fact again tends to prevent any such cogging. We have already pointed out that in ordinary polyphase in-

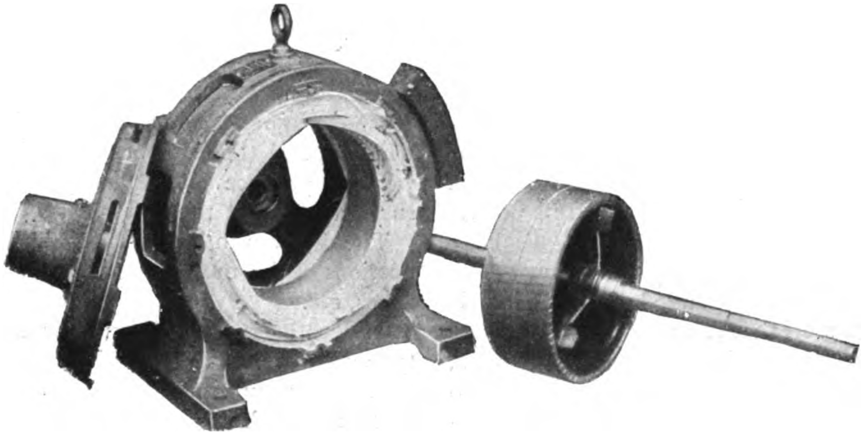


FIG. 560.—LANGDON-DAVIES SINGLE-PHASE MOTOR DISMANTLED.

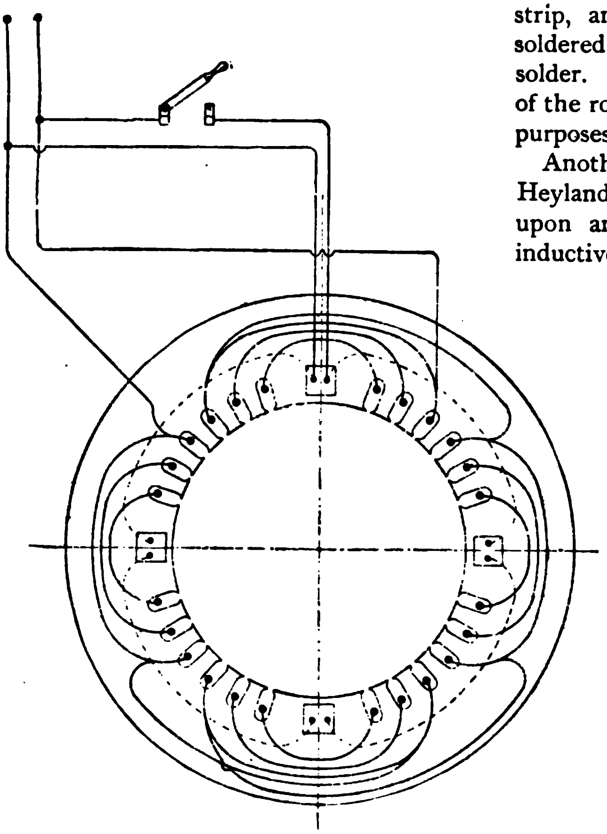


FIG. 561.—SCHEME OF HEYLAND'S STATOR WINDINGS.

duction motors, the same number of slots or any close multiple of the same number of slots should not be used, but in these single-phase motors it is more important still that close attention be paid to this point.

A more recent design of split-phase motor by this firm is shown complete in Fig. 559 and dismantled in Fig. 560. It will be seen that the rotor has undergone some changes, it is no longer wire-wound, but, as a matter of fact, consists of a laminated core having straight narrow slots milled into its periphery, into which strips of copper are fitted edgewise ; the ends of these copper strips are bent over against a brass ring at the end of the core discs until they overlap the end of the preceding strip, and, when all are in position, are soldered to form a solid mass with hard solder. Projections cast upon the spider of the rotor circulate the air for ventilating purposes.

Another type of single-phase motor is the Heyland motor, which depends for starting upon an auxiliary coil forming a highly inductive branched circuit at starting, and thus producing a displacement of phase between the two branches. Fig. 561 shows diagrammatically the stator windings of the Heyland motor. The main single-phase winding is wound in six slots per pole (this being a four-pole motor), while the starting coil is threaded through the four large closed slots, one large slot to each pole. The slots which carry the "running" winding, it should be specially noted, are partially open, in accordance with the usual practice.

The effect of closing the slots through which the starting coil is wound, is to increase the self-induction of this winding. This starting coil is, as it were, a choking coil built in with the motor frame, and the difference in phase of the magnetic field produced by this winding, and the field set up by the main winding, produce a rotating field which is sufficient to start the motor.

The diagram in Fig. 562 shows the connections of the motor with starting resistances, etc.

The rotor is of the three-phase wound type with the usual three-phase resistance for starting purposes, and it will be seen that there is also a resistance, R (used only at starting, as are the rotor resistances), included in the circuit of the running coils.

This external resistance, R, in the running coils, cuts down the starting current to a minimum when the motor is starting up

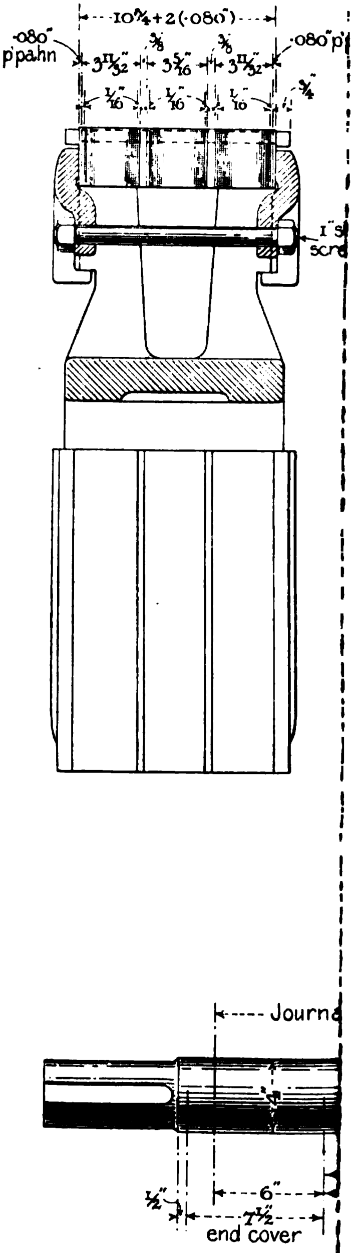


PLATE XII.—DETAILS OF 90 K.V.

light, but is not necessary and may be short circuited when the motor is required to start against a heavy load. The switch is shown in the starting position, and when the motor has got under way the handle is turned in a clockwise direction, gradually cutting out the resistances in the rotor circuit, until in its final position it not only short circuits the slip rings in the usual way, but also bridges across and short circuits the resistance, R, and at the same time cuts out the starting coils, *s s*.

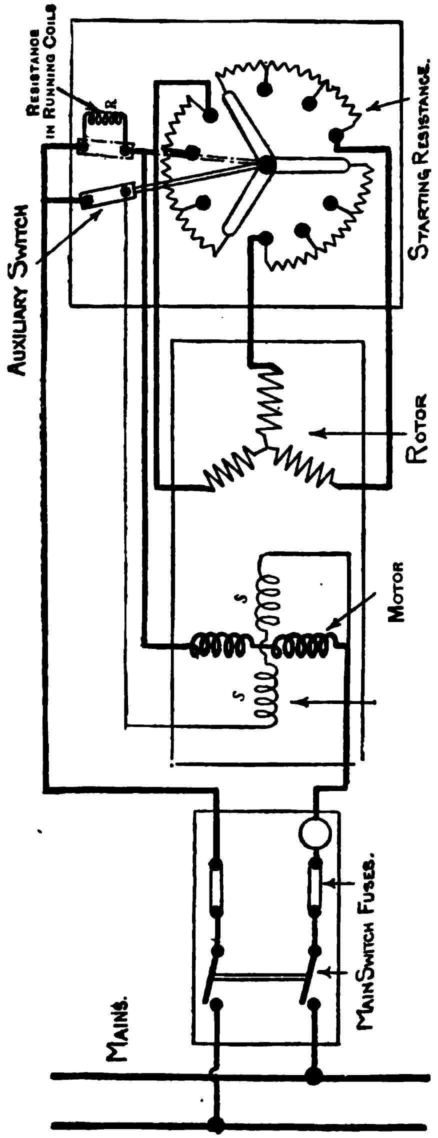


FIG. 562.—STARTING CONNECTIONS OF HEYLAND MOTOR UNDER "NO LOAD."

The actual four-pole type of this motor is shown in Fig. 563. Four terminals will be seen, two belonging to the running single-phase winding and the other two connected to the auxiliary starting coil.

These motors start up light with four-fifths of full load current, and with twice full load current will start against ordinary load when the frequency is not above 60 ∿.

An interesting example of a large single-phase induction motor by Messrs. Johnson and Phillips, Limited, is shown in Plate XII. This motor forms the alternating current side of the single-phase to direct-current motor generator set which is shown in Plate XIV. The details of the stator housing, stator core, and rotor are shown here by the full-dimensioned drawings.

This motor has no phase-splitting arrangement and therefore is not self-starting, but is started up by an auxiliary single-phase, self-starting motor (with starting coil for splitting the phase).

This single-phase motor (which is not shown in the drawing) is belted to a small pulley keyed on to the main shaft.

It would have been possible in this case to have dispensed with the small starting motor and made the main motor self-starting, but probably limitations were imposed upon the consumers by the supply company which made it impossible to start up the large motor direct, owing to the very large current at low power factor which would of necessity have to be drawn from the supply mains at the moment of starting. The auxiliary motor is started light, and the belt then throws in through a friction clutch and, finally, when the whole set is running at full speed the supply is thrown on the main motor.

SINGLE-PHASE COMMUTATOR MOTORS.

The single-phase motors which we have so far described have all been of the induction type. They are nothing more or less than the ordinary polyphase induction motors, so modified in internal design, and with the addition of devices to produce by phase splitting an apology for a rotating field, that they are enabled to start up against light load with a more or less extravagant expenditure of current on a low power factor.

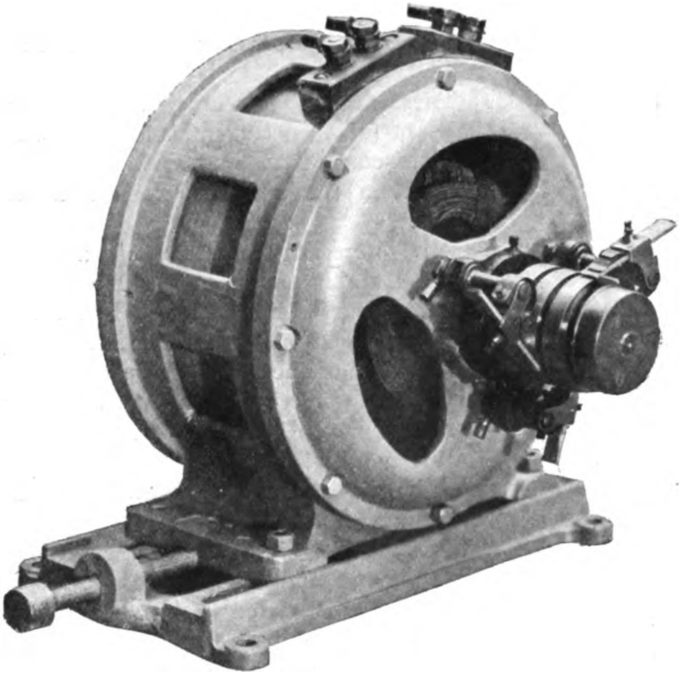


FIG. 563.—HEYLAND SINGLE-PHASE INDUCTION MOTOR.

As we have seen they have had only a limited application, due to their bad starting qualities, great weight and low efficiency as compared with either the two- or three-phase motors or continuous-current machinery.

All induction motors are fixed speed machines and, as we have seen, speed variation can only be obtained by either designing the motor to have a very low efficiency (and this method of obtaining a slight speed variation is only appreciable to the very smallest motors), by wasting a large amount of energy in external resistances, or by the almost impracticable device of changing the number of poles.

Polyphase motors, and to a lesser degree the single-phase induction motor, have had a wide application for constant speed work; but for many years when a motor was required for variable speed work there was no alternative but to employ the direct-current machine. The polyphase motor has, it is true, been applied to traction work on a large scale on the Continent, but this has been largely in the nature of constant speed work, *i.e.* mountain railways and similar installations, which do not necessitate frequent stops and where, after starting, the motors run at their only true economical speed, that is, just below synchronism.

The starting of polyphase and single-phase induction motors under heavy load is very uneconomical, due, of course, to the fact that much of the energy is wasted in the starting resistances, though the more efficient method, tandem control, where applicable, enables the polyphase traction motor to more nearly approach the economy effected by the series parallel control of direct-current traction motors, but is much inferior in actual practice.

The direct-current series traction motor is very satisfactory except as regards its voltage limitations.

It seems likely with the introduction of auxiliary poles, which are now being tried with traction motors, that it will be possible to raise the maximum voltage from the present 600 volts to about double this, 1,000 or 1,200 volts, and still obtain satisfactory commutation, but much higher voltages are hardly likely owing to the constant tendency to "flash" round the commutator, and this is especially true of traction motors which run without attention for considerable periods.

High voltages are used on the trolley in polyphase traction, in fact, it is quite possible to run up to 4,000 or 5,000 volts, or even much higher if necessary; and the voltage can be reduced by transformers or applied at high pressure direct to the stators of the driving motors—it is only a question of insulation. But one of the great disadvantages of the polyphase system is the necessity of using at least two overhead wires with the accompanying duplication of collectors and complication of the overhead line construction.

The very high voltages and the simplicity of the overhead gear constitute the important features in favour of single-phase traction. With the single-phase system a single overhead wire no larger than the ordinary trolley wire can be used to transmit any required amount of power, the voltage being 3,300, 6,600, or even a contemplated 11,000 volts on the line.

We have not space here to give a detailed description of the different types of single-phase commutator motor which have been developed. All these motors possess more or less the valuable characteristics of the direct-current series motor, the high starting torque, and speed rising with decrease of load. It was pointed out in Chapter IV. that the ordinary direct-current series motor could be run on a single-phase supply if it were sufficiently modified, and we shall therefore describe the representative motor of this type, the single-phase series commutator motor which was developed by the Westinghouse Company of America, under the direction of Mr. Lamme, and which is now manufactured in this country by the British Westinghouse Electric and Manufacturing Company. Several other types of alternating commutator motors have been described by their inventors in the technical press during the last three or four years.

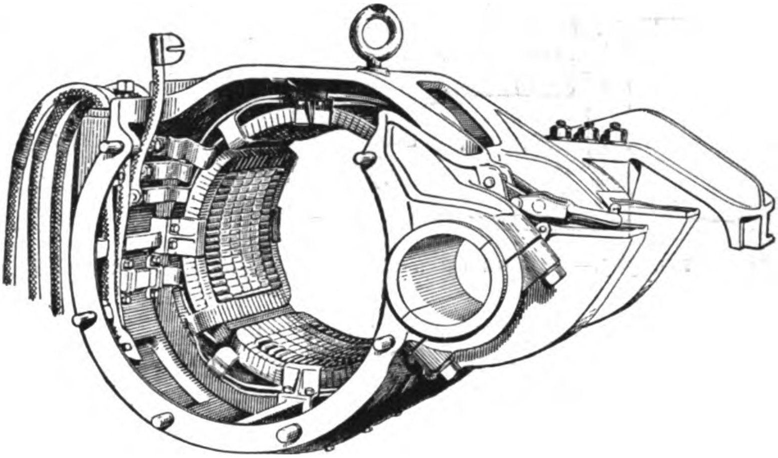


FIG. 564.—FIELD SYSTEM OF WESTINGHOUSE SINGLE-PHASE COMMUTATOR MOTOR FOR TRACTION.

A four-pole single-phase Westinghouse traction motor is shown in Fig. 564, the armature being removed from the casing together with the front and rear end housings.

The poles are not so well defined as in the case of a direct-current field, but two of the four main field coils are easily distinguishable, and the relatively small amount of copper in these coils should be especially noticed, and, as can be judged by the external dimensions of the case, the total amount of active iron in the field is relatively very small. The poles are slotted, each with eighteen closed slots to receive the compensating winding which is used to balance the distorting effect of the armature conductors lying under the poles.

The main field coils, compensating winding, and armature are all in series, and consequently both field windings must be of conductor of heavy cross section.

The external cast steel case forms no part of the magnetic circuit as it does in the direct current traction motor, but serves merely as a retaining case for the laminated field, in this respect being similar to induction motor and alternator construction.

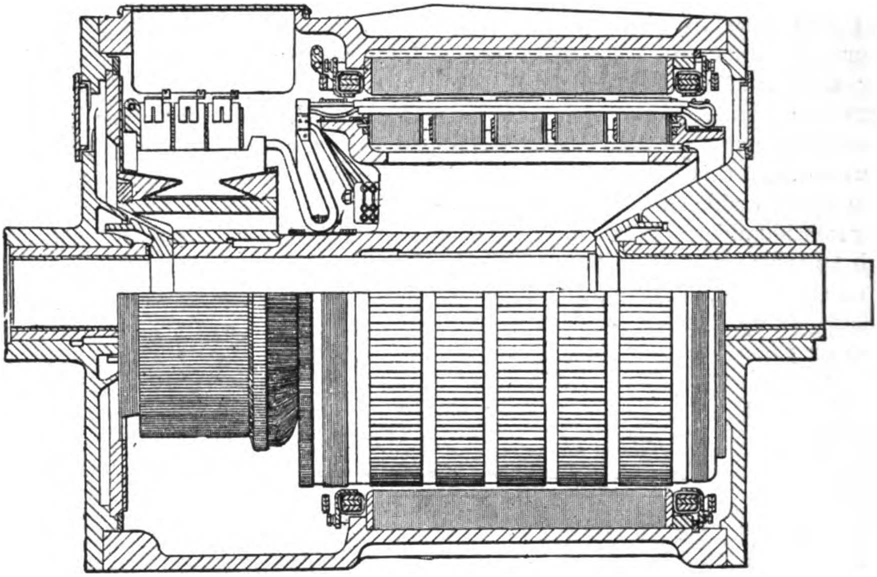


FIG. 565.—SECTION OF WESTINGHOUSE SINGLE-PHASE COMMUTATOR MOTOR.

The armature, which is not shown in the illustration is, in external appearances, very similar to that of the ordinary direct-current motor, but there is one difference, which is of supreme importance, and without this distinctive addition the operation of such a motor would be impossible. Fig. 565 gives a sectional view through the armature and field of a Westinghouse motor (this however being of one of the old types of alternating-current motor).

The armature conductors are embedded in slots in the armature core, but are connected up to the commutator through *high resistance* leads.

In the motor shown, the leads are bent back at the commutator end of the armature, thus giving a considerable length of resistance, through which the current from the armature has to flow. Other arrangements of these resistance leads are possible, for instance, they may be connected to the rear end of the armature winding (remote from the commutator) and may be brought underneath the armature core through the spider construction, to the commutator bars.

These high resistance leads are of German silver or of a similar high resistance alloy.

From our brief description of the motor it will be seen that the departure from orthodox direct-current design is considerable, and we will therefore briefly consider the reasons which necessitate such construction as we have described, and particularly deal with the necessity for the addition of the high resistance commutator leads.

We mentioned in Chapter IV. that it had been known for years that very small direct-current motors could run (though very imperfectly and with heavy sparking at the brushes) on alternating current, but for a long time the difficulties in designing a practical motor were thought to be insuperable, and these were for the ordinary type of series-wound motor, the following :—

(*a*) Prohibitive sparking at the brushes.

(*b*) Very low power factor.

We will deal with these points in the above order and show how by suitable, and in many cases radical, changes in design and construction, the difficulties have been overcome.

The sparking which is quite prohibitive when it is attempted to run any ordinary good, direct-current motor with alternating current is due to the *transformer* action, which does not exist in a direct-current machine.

We have already pointed out that the field must of course be laminated exactly as with a transformer or alternating current electromagnet, to prevent excessive waste of energy and extreme heating through the eddy currents set up. The motor at standstill is nothing more or less than an alternating-current transformer, the alternating field threading through the armature as part of its magnetic circuit.

Now we have to consider the armature winding. We know that this forms a closed circuit round the armature, but if the winding itself be symmetrical, and if we consider the armature *without brushes on the commutator*, it will be at once seen that although the winding is short circuited on itself, yet no current will flow and no energy will be dissipated in this closed-up winding, because all E.M.F.s generated in it neutralise one another. If it were not for this fact it would be impossible to make a single-phase commutator motor.

For, if we take a bipolar field excited with alternating current and consider a simple ring armature put into the field, we see that all the flux entering this armature from the N pole and cutting one side of the armature winding will similarly cut an equal number of turns of the winding when the flux leaves the armature and enters the S pole of the field.

The flux cuts both halves of the armature winding in the same direction, and therefore sets up E.M.F.s in the armature in the *same direction* in *both sides* of the winding. These E.M.F.s are equal and oppose one another, and therefore there is no resultant voltage to produce a current in such a closed winding.

But we started out with the assumption that all the brushes were lifted off the commutator. If we now place brushes on the commutator the condition of affairs is altered, and in the coils short circuited by each brush will be induced an E.M.F. due to the transformer action of the field, and it is this transformer action on the armature coils short circuited by the brushes which causes the prohibitive sparking which we have mentioned, if some special means are not adopted to overcome it.

The high resistance commutator leads which we have described suffice by the high ohmic resistance which they introduce into the short-circuited armature coil (at the moment when the coil is bridged by the brush) to cut down the value of the spurious short-circuit current to a reasonable value, and thus prevent any injurious sparking and loss of energy.

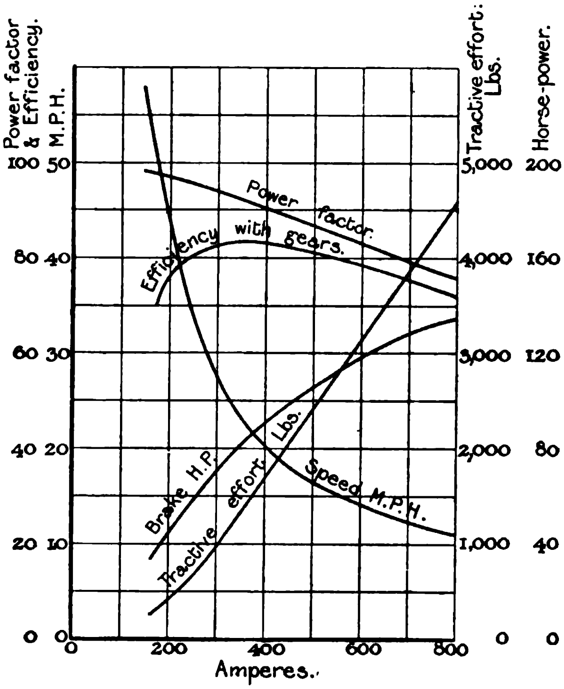


FIG. 566.—PERFORMANCE CURVES OF SINGLE-PHASE COMMUTATOR MOTOR.

The compensating winding wound through the pole faces is necessary for good commutation because of the very weak field which has to be made use of in these motors. The employment of a very weak field is necessary in order to keep the self-induction as low as possible and thus obtain a good power factor, and this weak field necessitates a high ratio of armature to field ampere turns, and so the distorting effect of the armature currents must be carefully allowed for, and this is best effected by such a compensating winding.

The currents flowing in the compensating winding are in the opposite direction to the armature currents, and by suitable adjustment of the compensating ampere turns, the distorting component of the armature ampere turns can be almost completely neutralised.

The compensating winding adopted, to some extent reduces the inductance of the armature, and in any case the inductance of the armature winding would naturally be less than that of the field, so that to obtain good power factor it is absolutely necessary to reduce the field flux as much as possible.

This explains the use of such small main field coils in the Westinghouse motor we have illustrated.

The performance of these single-phase motors is, as regards starting effort and speed variation with load, almost identical with the direct-current series motor.

Fig. 566 gives the performance curves of a Westinghouse motor for 225 volts, 25 ∿ 18 : 65 gear ratio and 36 in. wheels.

It will be noticed that the efficiency reaches a maximum value of about 83 per cent. which is not quite as high as would be obtained with the corresponding direct-current motor of the same output.

This slightly lower efficiency is due to the extra losses taking place in the iron in the alternating-current motor, that is, the transformer losses which occur both in field laminations and armature, and not, as is the case with the direct-current motor, only in the armature.

The power factor curve drops with increasing current, but at low current input and high speeds the power factor is very large, reaching as high as 94 per cent. at 300 amperes, corresponding to a speed of 27 miles per hour approximately.

The power factor is lowest with the heavy currents which would be used at starting, but high power factor under normal running conditions is of course of much greater importance.

The reason why the power factor decreases with increasing current input is simple, for since the field and armature each possess an inductive component due to their acting as choking coils, they will evidently cause a higher inductive drop with high currents ; for the increase of flux in the field will be (neglecting saturation) proportional to the ampere turns, and the inductive voltage set up across the field will vary almost directly with the increase of current, and this will cause a continual lowering of the power factor as the current increases.

The motor, of which we give performance curves, operates at 225 volts, and this low terminal voltage is characteristic of this type of motor.

This low voltage has great advantages, for there is said to be a complete absence of any tendency to flash over, and it is of course perfectly simple on alternating-current operation to get any voltage desired at the motor terminals by means of a step-down transformer ; in fact, the speed regulation of motors is generally effected by simply applying different voltages to the terminals from a number of taps on the step-down transformer.

These motors run equally well on direct current, and there are several lines already in existence in America where the same motors are frequently run over both alternating-current and direct-current systems without any inconvenience whatsoever.

CHAPTER VII.—MOTOR GENERATORS AND ROTARY CONVERTERS.

MOTOR GENERATORS—THE SYNCHRONOUS MOTOR GENERATOR—ROTARY CONVERTERS—INDUCTION MOTOR GENERATORS—EXAMPLES OF MOTOR GENERATORS—EXAMPLES OF ROTARY CONVERTERS.

MOTOR GENERATORS.

It is frequently found necessary to change the nature of an electrical supply; either to convert currents of one *type* into another, as, for instance, alternating current into continuous current, or to change the *pressure* of an alternating or continuous current supply. It is also sometimes necessary to change the *frequency* of an alternating supply for particular purposes, or even in some cases to make use of devices for changing the number of phases in an alternating current circuit.

As regards continuous currents, the only case of transformation which occurs is occasioned by the necessity of altering the *pressure* of the supply. As continuous currents are not distributed usually at a greater pressure than 600 volts, and then generally by means of the three-wire system (giving a pressure of half the maximum available at any point, and thus the consumer has for the usual pressures of 440 or 500 volts across the "outers" of the system, 220 or 250 volts available between an "outer" and the "middle" wire), we may say that practically it is only when very low voltages are required that resort is made to any special apparatus for changing the pressure.

Pressures of under 220 volts are sometimes required for such work as charging the batteries of electric motor cars, for charging ignition cells, or for general manufacturing purposes, such as for electro-plating and other electro-chemical industries.

Such pressure transformation is effected by means of a motor generator, which consists simply of a continuous-current motor wound for the supply pressure, mechanically coupled to a dynamo which supplies a much heavier current at the lower pressure; and the most important consideration in this case is that the transformation shall be effected with a *high efficiency*.

Coming to alternating currents, there is a much wider field for the employment of motor generators. The commonest case, and one which very frequently occurs in practice, is the transformation of a high tension alternating current supply into continuous current for distribution for traction or lighting.

The transformation may be effected in the three following ways:—

(1) By means of a synchronous motor coupled to a continuous-current generator.

(2) By means of a rotary converter.

(3) By means of an induction motor coupled to a continuous-current dynamo.

All these three methods are extensively used, and the best combination to adopt in a particular case depends entirely upon circumstances.

THE SYNCHRONOUS MOTOR GENERATOR.

This type has many advantages, but one very serious disadvantage, namely, that a synchronous motor is not *self-starting*. If the set, therefore, has to be started up from the alternating current side, this must be effected by means of a small auxiliary induction motor, but in those cases where continuous current supply is available, the above disadvantage to some extent disappears, as the set can then be started by using the direct-current dynamo as a motor; but even in this case it is usual to have some arrangement for starting up from the alternating side, if for any reason (such as all the converters having to shut down by reason of a breakdown), the continuous current supply is not available for starting up a set.

The synchronous motor possesses the great advantage that it can work at unity power factor, or by adjusting the field excitation it can even be made to give a leading current, and thus help to increase the power factor of the whole circuit.

The synchronous motor differs in no way from the ordinary alternator; in fact, in most cases, makers use their standard alternators as synchronous motors for motor generator sets. The continuous current for exciting the field of the synchronous motor is, of course, easily obtained, in the case of the transformation by the motor generator from alternating to continuous current, by taking the current for the field excitation from the continuous-current side after the set has been run up to speed.

The remarks which we have made about the parallel running of alternators apply with equal force to the case of a synchronous motor running in step with the alternating supply. Hunting troubles occur and damping coils are frequently employed, while all the usual precautions as to throwing the motor in with the supply must be taken as is the case in paralleling alternators.

The synchronising devices and the switch gear employed are similar to the alternator paralleling gear.

ROTARY CONVERTERS.

The rotary converter is a combination in one machine of a synchronous motor and continuous-current dynamo. The machine is, in fact, in form a multipolar dynamo, fitted, in addition to the commutator, with slip rings connected to suitable points in the armature winding; enabling alternating currents to be supplied to the armature, so that when running at full speed the machine is practically a synchronous motor, while continuous current can then be drawn from the commutator in the usual way. The action of the rotary converter is somewhat complex, but we only have space here to go into the general theory of the machine.

The action of the machine (usually described briefly as a "rotary") is best understood by keeping in mind the great fact that the current in all generators, alternating current or continuous current, is primarily alternating, with the sole exception of homopolar machines. In continuous-current machines the commutator exercises the function of transmuting the alternating currents generated in the armature conductors, into unidirectional currents in the external circuit. When a machine is provided with both slip rings and a commutator, and is used to deliver an alternating current from the rings and a continuous one from the commutator, the first question that arises is: what is the ratio between the two E.M.F.s? The answer to this question will depend very largely upon the distribution of the magnetic flux, since the alternating value is the root mean square value and this, with a fixed maximum, will vary with the shape of generated E.M.F. wave. If the field distribution were sinusoidal, and if the winding were a simple Gramme ring winding it is easy to obtain theoretical values. The E.M.F. in any wire will follow a sine law and will be sin θ if θ is the angle as indicated in Fig. 567, and E the maximum E.M.F. in one wire during a revolution. If there are s wires on the periphery and connections from slip rings are made to two points, a and b, including an angle α, the total E.M.F. at the instant indicated will be

$$\int_{\theta}^{(\theta + \alpha)} \frac{s}{2\pi} \mathcal{E} \sin \theta \, d\theta$$

$\mathcal{E}$ being the maximum E.M.F. per turn, or $\frac{s}{2\pi} \mathcal{E} \left(\cos - \cos \theta + \alpha\right)$, and with a sine wave the mean square volts will be

$$\frac{s^2 \mathcal{E}^2}{4\pi^2} \int_0^{2\pi} \left\{\cos \theta - \cos (\theta + \alpha)\right\}^2 d\theta,$$

that is $\frac{s^2 \mathcal{E}^2}{2\pi}\left(1 - \cos \alpha\right)$.

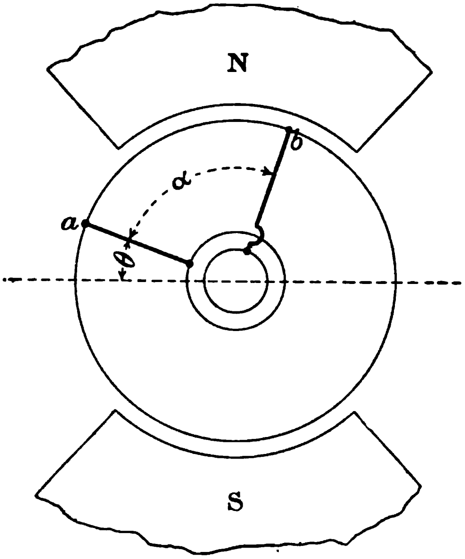


FIG. 567.—DIAGRAM FOR OBTAINING VOLTAGE RELATIONS IN A ROTARY CONVERTER.

Similarly on the commutator the E.M.F. will have the steady value of $\frac{s}{\pi} \mathcal{E}$. It is obvious that in such an armature only delta connections are possible, so that the values of α for single-phase, two-phase and three-phase working are π, $\frac{\pi}{2}$ and $\frac{2\pi}{3}$ respectively for the above case, so that the ratios would be $\frac{1}{\sqrt{2}}$, $\frac{1}{2}$ and $\frac{1}{2}\sqrt{\frac{3}{2}}$ the numerator representing the slip ring and the denominator the commutator voltage. Hence with 100 volts on the commutator there would be 70·7, 50, and 61·23 volts between slip rings for the one-, two- and three-phase cases respectively.

In the case of actual machines the flux distribution is not accurately known, and is certainly not a sinusoidal one, neither is the winding a simple Gramme ring, hence the above results cannot be applied at all closely. Experiment shows, however, that the results of the breadth coefficient of the winding, and the flat-topped wave of flux distribution, usually combine to give values that happen to come fairly near those calculated on the above assumptions. The simplest method of considering what occurs in reference to current strength is that used by Dr. S. P. Thompson in a paper read before the Institution of Electrical Engineers in 1898, from which paper Fig. 568 is taken.

The diagrams in this figure relate to a case of a three-phase converter of which the continuous-current output is 100 amperes at 100 volts. From what has just been said it will be seen that the three-phase voltage will be 61·2 theoretically (in practice it will more probably be 62 volts). With delta connections this will be 61·2 line volts and, if we assume no losses in the machine, and there are 10 kilowatts on the commutator side, there will be 3·33 kilowatts in each phase. This will demand a current of 54·4 amperes in each phase and a line current of 94·3 amperes. We can now, therefore, calculate the current generated in each phase at various stages in one revolution by assuming a sine wave of current, and drawing a number of positions for, say, a two-pole machine at given changes of angular position. If the angle is reckoned as θ from some starting point the three currents $C \sin \theta$, $C \sin (\theta + 120^\circ)$ and $C \sin (\theta + 240^\circ)$ respectively where C has the value $\sqrt{2} \times 54{\cdot}4$, the slip-ring currents will have similar values, but all multiplied by $\sqrt{3}$ and attention being paid to phase angle.

The point at which the current in any phase will be 0 is clearly where its E.M.F. is 0, and since each phase comprises one third of the winding, this can only be when the phase is divided into two equal parts generating opposing E.M.F.s. This is the fourth position in the top row of Fig. 568. This top row gives in the first diagram the continuous-current flow considered by itself, and in the subsequent diagrams the three-phase currents considered by themselves, while the lower row gives the combination of the two.

Care must be exercised over the directions. The three-phase currents are to be motor currents while the continuous-current is to be *qua* generated. Hence the latter have a

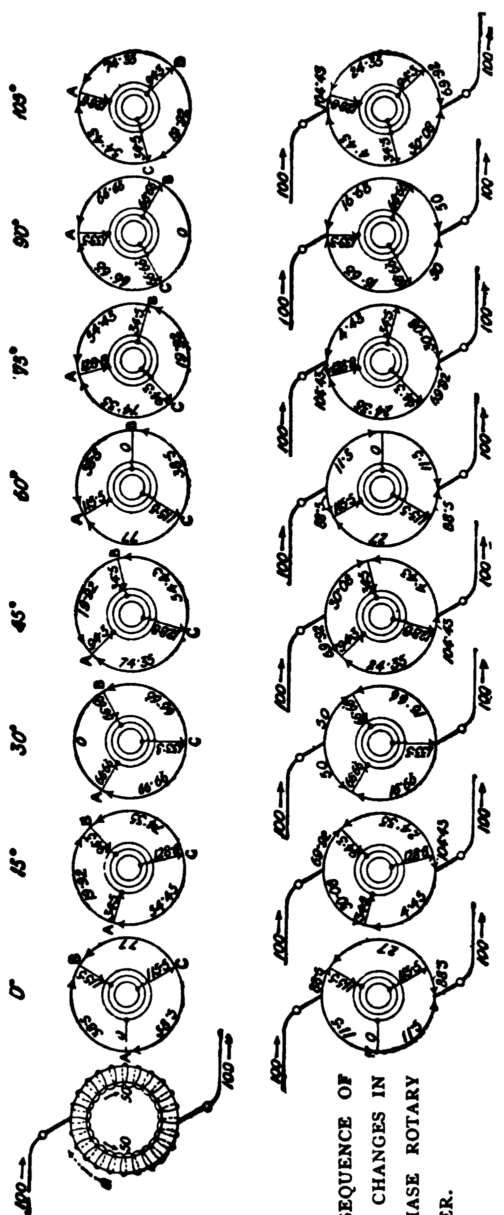


FIG. 568.—SEQUENCE OF CURRENT CHANGES IN THREE-PHASE ROTARY CONVERTER.

sign similar to the E.M.F., while the former have always a sign opposed to the E.M.F. The dotted arrow indicates the direction of rotation and the polar axis is assumed to be horizontal; the E.M.F. is shown by the arrows indicating direction of continuous-current flow in the first diagram, viz. downwards on each side.

Considering now the case at the instant marked 30° the current and E.M.F. in the top phase are both zero, and the current in the two other phases will therefore be, by calculation as above explained, $\sqrt{2} \times 54{\cdot}4 \times 0{\cdot}866$, *i.e.* 66·66, and the sign of each must be circumferentially upwards. This settles the current at each slip ring, and by proceeding similarly to the left and right the diagrams are completed for angular changes of 15°. It only remains then to superpose a constant current of 50 amperes as in the first diagram upon all the subsequent eight, and we obtain the lower row of figures for the actual current at instant considered.

Rotary converters may be either shunt or compound wound, according to circumstances, and when used for supplying continuous currents for traction purposes, are similar to the ordinary traction dynamo, *i.e.* compound wound. As rotary converters are practically synchronous motors, it follows that they are not self-starting from the alternating current side.

As with the ordinary motor generator sets, a starting motor, direct coupled to the shaft of the converter, is frequently used, or, of course, the starting can be easily effected from the continuous-current side.

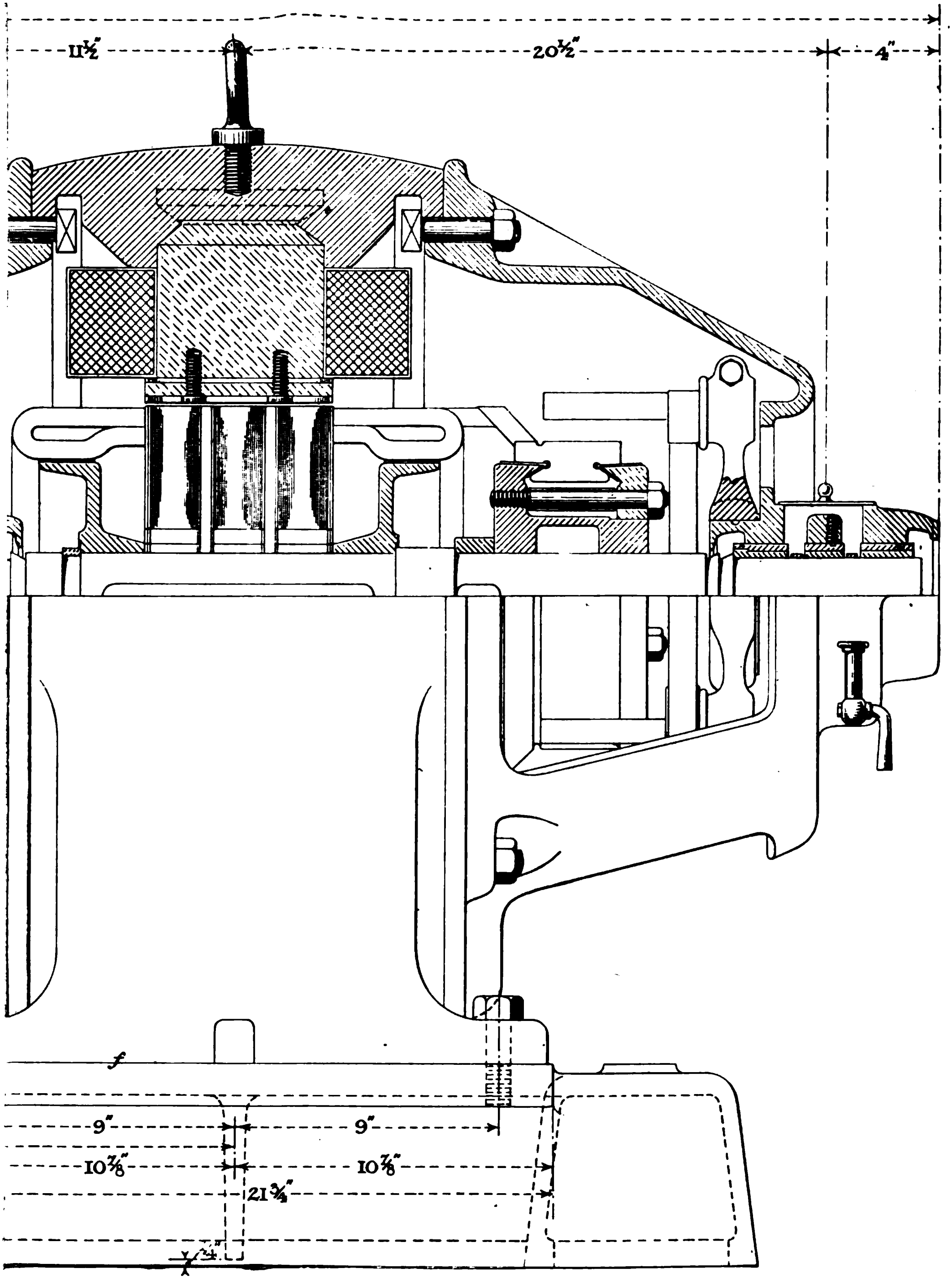
A third method is to start from the alternating-current side, the machine starting up as an induction motor, for under suitable conditions, the action of an induction motor may be simulated and the converter successfully run up to speed. This is, of course, only possible with two- or three-phase supply, as an approximation to a rotary field would not be possible with single-phase current without some auxiliary phase-splitting arrangement.

The field winding plays no part in this method of starting up, the field is, in fact, broken in several places in order to prevent excessive rise of voltage due to the transformer action which takes place. The armature in this case acts like the stator of an ordinary induction motor, the field poles being the equivalent of an unwound rotor.

Eddy currents are induced in the pole faces, and, reacting on the armature, exert a starting torque which, under suitable circumstances, suffices to run the converter armature up to synchronous speed. There are, however, serious disadvantages in most cases to this method of starting, the chief of which is that a very heavy current, amounting to one and a quarter to one and a half times the full load current, is required, and at a very low power factor, which would often disturb the system to a prohibitive extent.

Rotary converters in common with the plain synchronous motor have to be synchronised with the supply before being switched on to the mains. This requires that the starting motor shall be able to run the set up to a slightly higher speed than the synchronous speed of the converter; and, as the starting motor draws its current from supply of the same frequency, it follows that its normal full-load speed must be greater than the synchronous speed of the rotary converter or motor generator set. The starting motor must, therefore, possess fewer poles than the converter, as, owing to the slip of the starting motor, there would be no possibility of its speed ever attaining the synchronous speed corresponding to the frequency of the supply.

Thus an eight-pole rotary converter or synchronous motor generator set will have



OF 30 H.P. AT 460 VOLTS. GENERATOR OF REVOLVING FIELD TYPE, 20 K.V.A.,

a six-pole starting motor and so forth. Difficulty occurs here in the case of a four-pole converter, as the two-pole starting motor will give altogether too high a speed, and in this case a single-phase series commutator motor has been sometimes used, these motors being similar to the series continuous motor, as we have already seen in Chapter VI., in their flexibility as regards speed variation.

The advantages of rotary converters compared with motor generators is that there is only one machine to effect the same purpose as two in the synchronous motor generator set, and consequently they are in most cases cheaper.

The efficiency is also higher than in the motor generator sets, but to put against these advantages we have the fact that in large sizes they are difficult to design for satisfactory operation at high frequency, 50 ∿ conversion often giving trouble. This is because the higher the frequency the greater the number of poles necessary, or the greater the speed, and this circumstance must in either case result in giving a high peripheral speed to the commutator, which introduces both mechanical and electrical difficulties. A lower frequency is much more favourable to the satisfactory operation of rotary converters; fewer poles are necessary for the same speed in revolutions per minute, and thus the diameter of the machine and peripheral speed can be kept low.

Hunting troubles occur in rotary converters, exactly as with synchronous motors, and the damping coils mentioned as being used on synchronous motors and alternators are also employed on rotary converters for exactly the same purpose.

INDUCTION MOTOR GENERATORS.

As the induction motor is self-starting, matters are much simplified, but the fact that the induction motor has a power factor considerably less than unity (90 per cent. being a good figure for a large induction motor) is a disadvantage, and the power factor will of course be very much lower when the set is running on a light load.

An improved form of induction motor generator is the "Cascade converter," which we shall presently describe.

EXAMPLES OF MODERN MOTOR GENERATORS.

In Plate XIII. is shown a small motor generator set by Messrs. Johnson and Phillips, Limited.

It consists of a continuous-current motor of 30 horse-power at 460 volts coupled to a 20 kilo-volt-ampere three-phase revolving field generator delivering current at 200 volts across the lines; the alternator is six-pole and 50 ∿, and the speed of the set is therefore 1,000 revolutions per minute. The motor is one of the firm's standard continuous-current type, similar to the motor of the same armature diameter, but of greater core length, and is described in Chapter III. The poles are of circular section mild steel bar cast in the cast-iron yoke, and laminated pole tips are employed.

The alternator has a cast-steel field with solid steel pole tips bolted on, and ample ventilation is provided by means of a duct through both field and armature core, and the field windings are piled up in order to make the most of the rather limited space available in such a small revolving field structure.

Both machines are self-contained, that is, each is provided with two bearings, and mounted on a common bedplate, a flexible coupling is used to minimise vibration if by any chance the two machines are not in absolute alignment, and all bearings are provided with oil rings and cocks, and gauges to show the level of the oil in the wells.

Another very interesting set by the same makers is shown by a sectional drawing in Plate XIV. There is an alternating-current motor of the single-phase induction type, driving a continuous-current dynamo giving an output of 66 kilowatts at a no-load speed of 770 revolutions per minute, and a full-load speed of about 750 revolutions per minute at 200 volts pressure, the dynamo being shunt wound. The induction motor used here is the same motor which has already been fully described in Chapter VI. The starting up of this single-phase motor is accomplished, it will be remembered, by means of an auxiliary split-phase starting motor, driving through a friction clutch on to the pulley at the end of the shaft of the set. The continuous-current dynamo has a massive cast-iron yoke with cast-steel poles bolted on ; the armature core is well ventilated by three radial ducts, and it will be noticed that ventilated field coils are used.

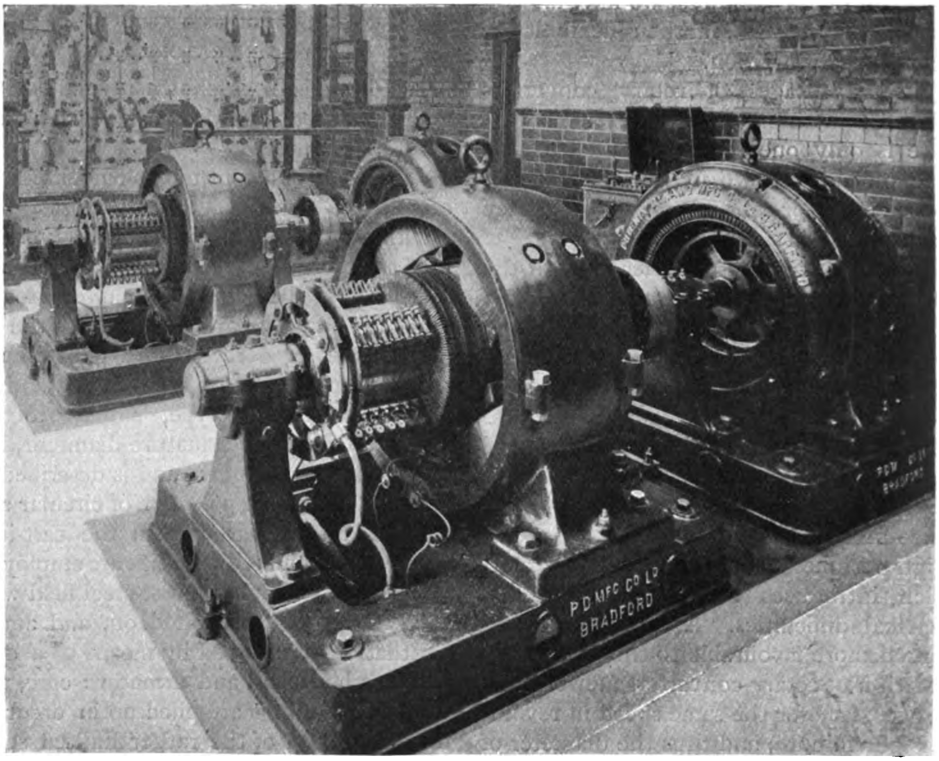


FIG. 569.—MOTOR GENERATOR SETS AT WEDNESBURY : TWO-PHASE MOTORS, SHUNT GENERATORS.

If we assume the efficiency of the dynamo to be 92 per cent., the rating of the motor will be

$$\frac{66}{\cdot746 \times \cdot92} = 96 \text{ horse power.}$$

The motor runs from a 200 volt single-phase supply, and if we take the efficiency of the motor at 90 per cent. and the power factor at 88 per cent. (both reasonable figures), we get an input of 90 apparent

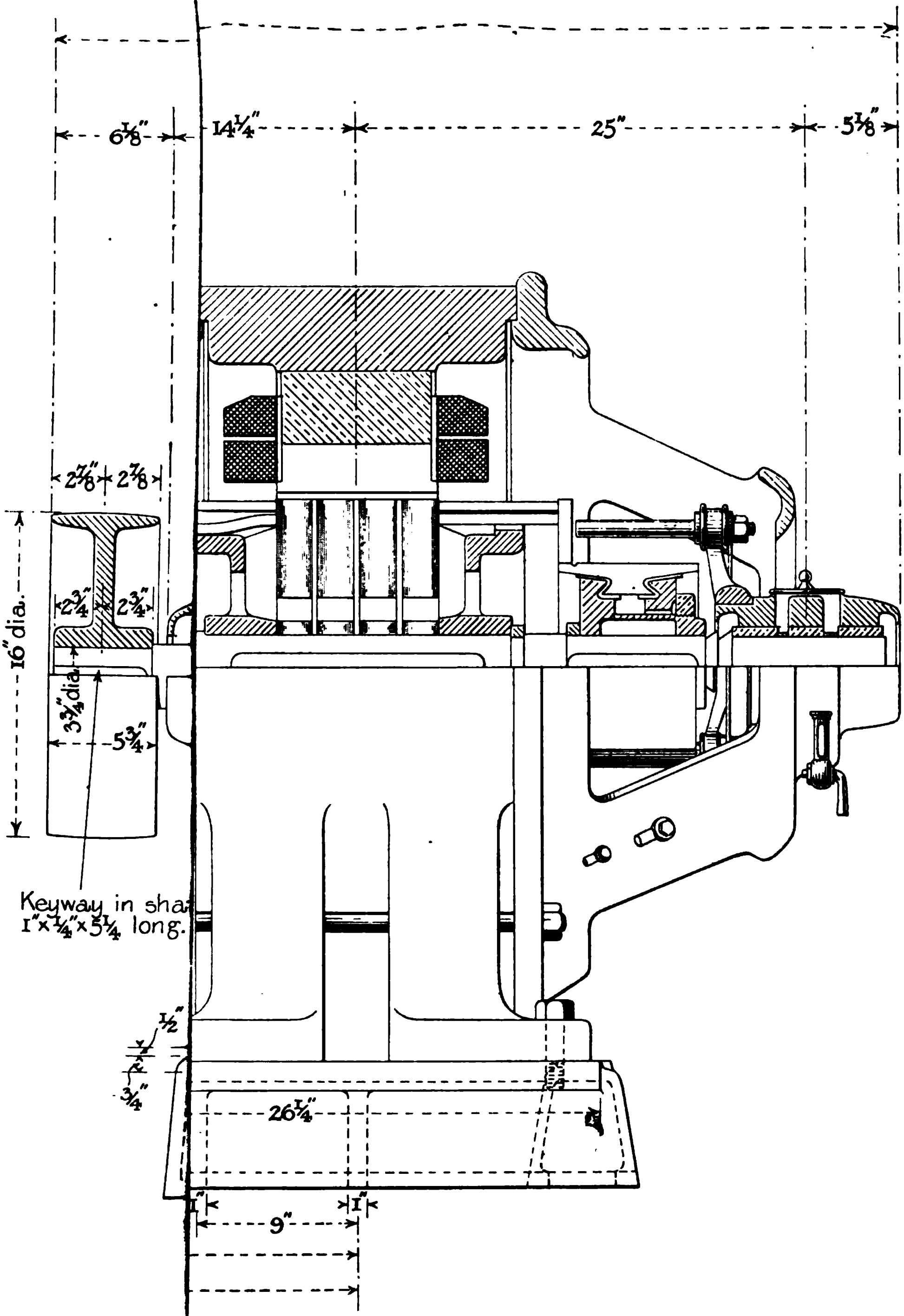


PLATE XIV.—SI 200 VOLTS; DIRECT-CURRENT GENERATOR 66 K.W., 200 VOLTS;

kilowatts into the motor at full load, or 450 amperes at 200 volts.

As single-phase split-phase motors will hardly start with less than full-load current against the friction of their own bearings, it will be seen that to have dispensed with the auxiliary motor would have meant a current of this magnitude or probably more being required at starting, and it would further have been necessary to have used a wound rotor instead of the short-circuited winding adopted.

A somewhat similar motor generator, in this case with a two-phase induction motor, is shown by a photograph in Fig. 569, illustrating two sets manufactured by the Phœnix Dynamo Manufacturing Company, Limited., and installed by them at Wednesbury, in March, 1904. The two-phase 125 horse power 50 ∾ 200 volt induction motor drives a 75 kilowatt 230 volt shunt dynamo, and the manufacturers state that the order was obtained largely on the basis of a high efficiency guarantee which was actually exceeded on test.

In Fig. 570 is shown a motor generator set with the same mechanical arrangement of three bearings, the two machines being mounted on a common bedplate. This set is by the Electric Construction Company Limited, and consists of a compound-wound continuous-current motor at 440 to 550 volts driving a 220 kilowatt 3,000 volt 50 ∾ three-phase generator running at 428 revolutions per minute. This is an unusual case of conversion, as it is rarely necessary to convert from direct current to polyphase alternating current, the opposite being usually the practical need. Upon the right hand side of the illustration may be seen a lever and screw arrangement, by which the stator of the alternating-current machine may be slid along the bedplate for inspection or repairs.

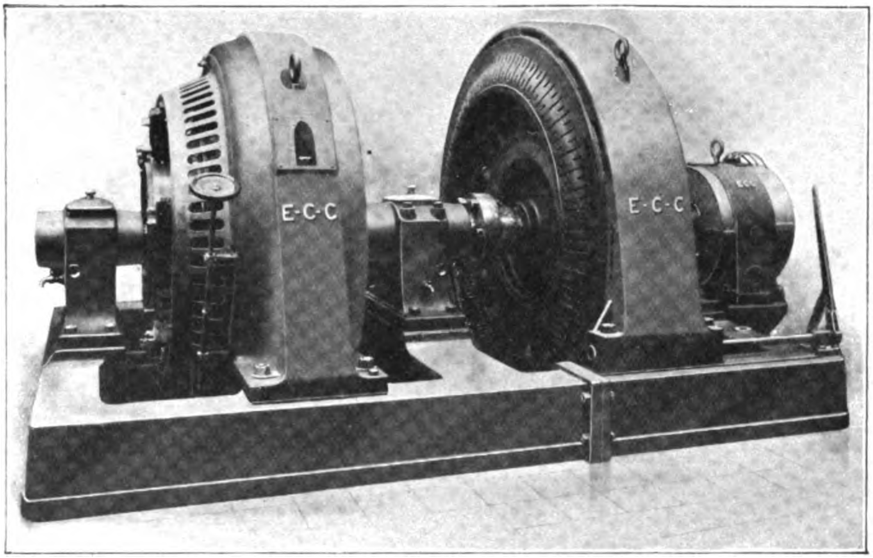


FIG. 570.—MOTOR GENERATOR SET: D.C. MOTOR 500 VOLTS, THREE-PHASE 3,000 VOLT GENERATOR.

EXAMPLES OF ROTARY CONVERTERS.

An 8-pole rotary converter by Messrs. Dick, Kerr and Company, Limited, is shown in Fig. 571. This rotary is compound wound, and has a number of tappings taken out from the end windings of the armature to the three slip rings for three-phase currents. There are twenty-four of these tappings, there being, therefore eight per phase; they are taken to the three rings from equipotential points under each pole.

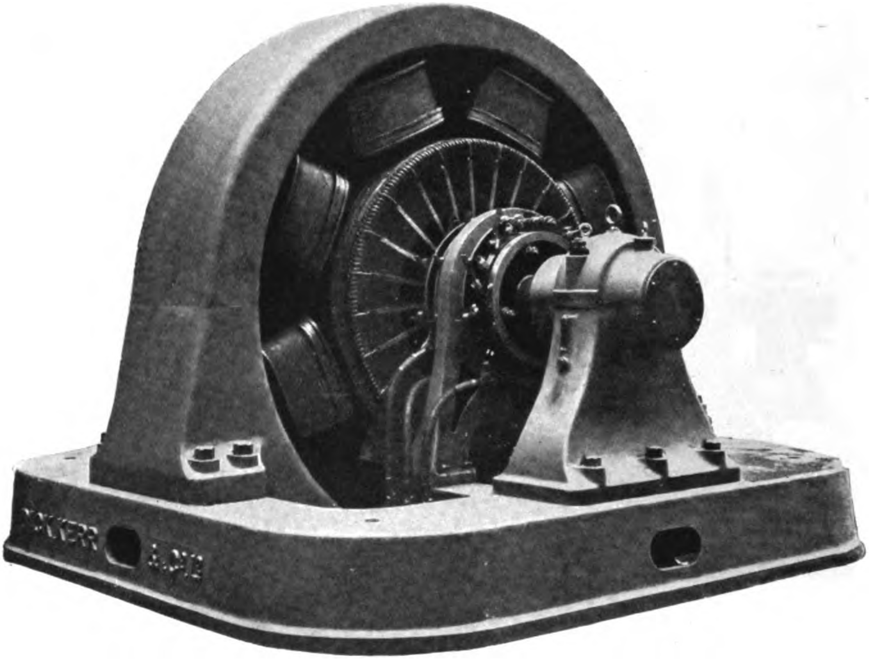


FIG. 571.—THREE-PHASE ROTARY CONVERTER, COMPOUND WOUND.

The slip rings on this converter are of gunmetal, supported in such a way as to afford ample facilities for ventilation and cleaning.

Copper brushes are used on the slip rings, as the currents with these large converters are usually too heavy to permit of the use of carbon brushes.

A 1,200 kilowatt rotary converter, made by the British Westinghouse Electric and Manufacturing Company, Limited, is shown by a photograph in Fig. 572. Three machines of this type are installed in the Moorgate Street sub-station of the Metropolitan Railway in London. The three-phase induction starting motor is shown in the foreground.

High-tension three-phase current is transmitted from Neasden at 10,500 volts, which is transformed in the sub-stations to 370 volts and then put into the rotaries, the voltage on the continuous-current side being 600. These converters have twelve poles, and as the frequency of the supply is $33\frac{1}{3}$ cycles, the speed is therefore 333 revolutions per minute. Compound winding is used, which, as we have mentioned, is usual for traction converters.

We shall, finally, describe one of the cascade induction motor converters manufactured under the Bragstad–La Cour patents by Messrs. Bruce Peebles and Company, Limited.

The cascade converter is a motor generator, the alternating-current motor being of the induction type coupled to a continuous-current generator in the ordinary way, but the windings of the rotor of the induction motor are interconnected with the armature winding of the continuous-current machine. The effect of these interconnections is that the set runs at *half* the speed for a given number of poles and frequency at which it would run if it were an ordinary motor generator. As the induction motor is thus running at half speed, or in other words, with 50 per cent. slip, a frequency of *half* the *supply frequency* will be induced in the rotor windings, and these low frequency currents entering the armature of the direct-current machine, cause it to operate practically like a rotary converter, only, of course, there will be no slip rings, the connections between the rotor of the induction motor and the direct current armature being carried through a hollow shaft.

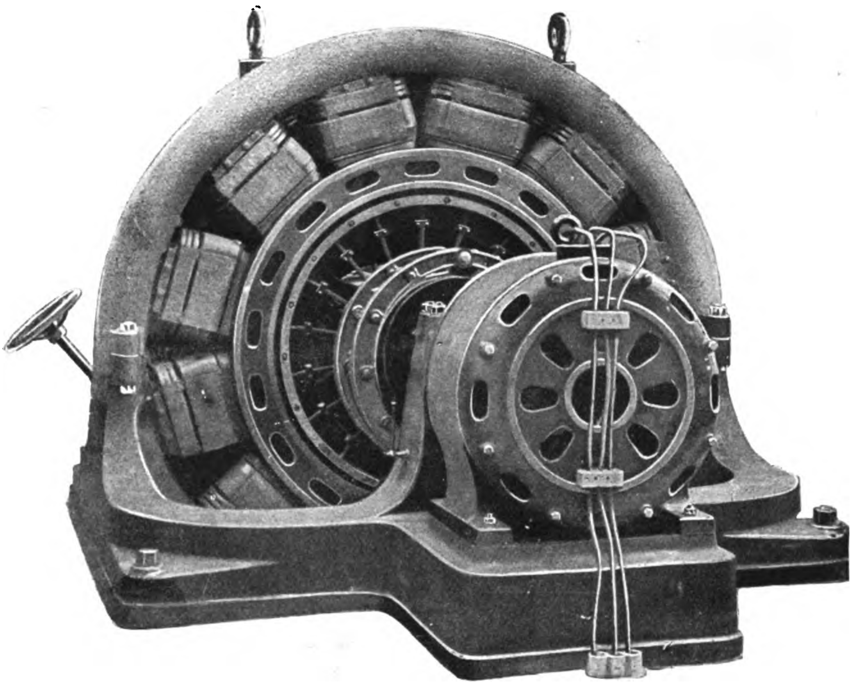


FIG. 572.—1,200 KILOWATT ROTARY CONVERTER WITH STARTING MOTOR.

The advantage of this arrangement is that the efficiency is higher than with the ordinary motor generator sets, the first cost should be less, and there are no hunting troubles. Fig. 573 gives a general view of a 500-kilowatt set, the connections to the direct current armature being plainly seen, cables are brought through radial holes in the face

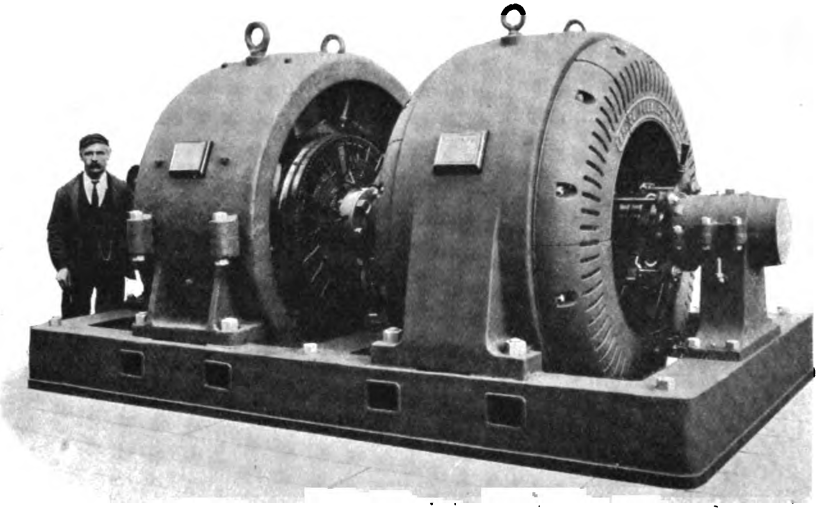


FIG. 573.—LA COUR CASCADE CONVERTER.

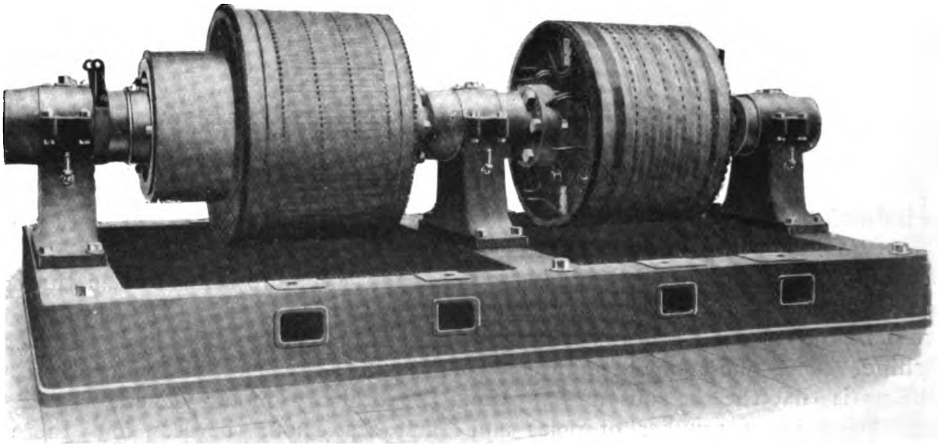


FIG. 574.—CONTINUOUS CURRENT ARMATURE AND THREE-PHASE "ROTOR ARMATURE" OF LA COUR CONVERTER.

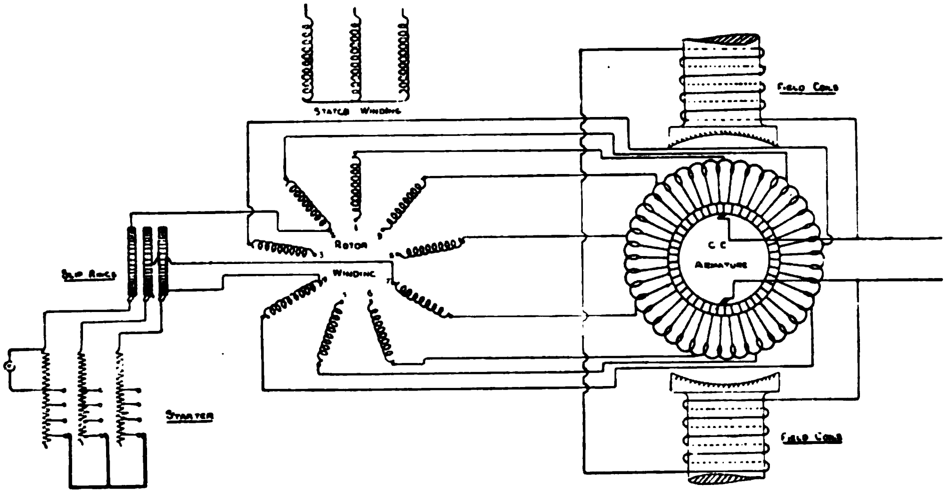


FIG. 575.—CIRCUITS IN LA COUR CONVERTER.

of the coupling; and in the view with the field and stator removed (Fig. 574), we can see the connections brought through the second coupling and connected up to the rotor of the induction motor. In Fig. 575 is shown diagrammatically the connections of the alternating-current and the direct-current sides of the set.

CHAPTER VIII.—MOTOR PRINCIPLES AND DESIGN TESTING.

THE FACTORS OF TORQUE—BACK E.M.F.—THE FACTORS OF SPEED—DISTRIBUTION OF POWER IN A MOTOR—EFFICIENCY—OUTPUT LIMITS—MOTOR CHARACTERISTICS—THEORY OF SINGLE-PHASE MOTOR—DESIGN TESTING—ARMATURE AND BRUSH RESISTANCE—SPEED MEASUREMENT—SEPARATION OF LOSSES—TEMPERATURE—TESTING OF IRON.

THE FACTORS OF TORQUE.

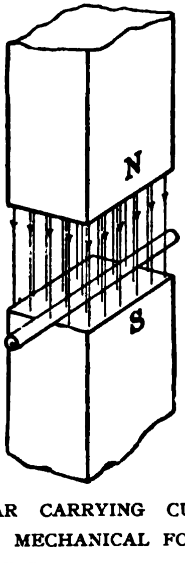


FIG. 576.—BAR CARRYING CURRENT SUBJECT TO MECHANICAL FORCE IN MAGNETIC FIELD.

THE fundamental principle at the root of the operation of all motors is to be found in the forces mutually exerted upon one another by materials associated with magnetic fields. In all but very few cases there are two distinct ways of considering the occurrence of the forces, although one will be found less simple of application than the other and less frequently used. The two views are referred to on pages 168 and 176 respectively, where we have, in the first case, the forces exerted so as to affect the iron (or steel) associated with a magnetic field, and, in the second case, the forces displayed upon the conductors which, *in combination with the currents they carry*, are associated with magnetic fields. As stated upon page 176, such conductors may be the subject of mechanical forces from magnetism however produced, as is further shown by the example of Fig. 576. The necessary conditions for the exhibition of such forces are that there shall be a conductor carrying a current, a magnetic field in which the conductor lies, and some component of the field at right angles to the direction of flow of current in the conductor. The direction of the force will then be in a line at right angles both to the flow of current and to the component of field just referred to. This brings us, in a word, to the converse of the rule set forth in Fig. 163, page 231, for abstract reasoning, and the evidence of direct experiment shows that if the flux and *current* are as indicated in Fig. 163, the force tending to produce motion of the conductor will be just *opposed* to the movement of the bar indicated by the thumb there. Abstract reasoning leads to this view, since if the motion were helped, instead of opposed, by the resulting force, it would increase in velocity, would generate more current by the increased E.M.F., and the current in turn would further accelerate the motion. With such a result, *in fine*, it would only be necessary to give a short-circuited motor the least movement and it would, of itself, run up to speed at once, and running faster and faster would *generate* more and more current in the short circuit to drive itself by, until it either burnt itself out or flew to pieces. The principle of conservation of energy, then, demands that the force due to a current and field shall tend to motion opposite to that which would produce that current.

An important corollary to this is that the movement produced by a current must generate in the bar an E.M.F. *opposing* the current. We may therefore make use of the rule given on page 231 and in Fig. 163 to determine the relations of flux, current and motion in the case of a bar, bearing in mind that some one, it does not matter which, of the directions must be reversed.*

Before passing on to a consideration of the magnitude of the force on the bar, it may be interesting to give one example of the other method referred to of regarding the relations of directions. We will apply it to the simplest case, that of a two-pole drum motor. If current is supplied to the brushes as indicated in Fig. 577, it is easy to see that the armature is itself an electromagnet, since it is encircled by a winding, all the turns of which on one side carry current in one direction and all those on the other side carry current in the opposite direction. In the diagram the field due to the field magnets is not indicated, but the dotted lines and arrow heads indicate the polarity of the armature regarded as an electromagnet. The polarity is further emphasised by the long dotted arrow and dotted N and S in the diagram. It must be clear that if the armature be a magnet with this polarity it must turn (as a motor) in a counter-clockwise direction by simple magnetic attraction and repulsion with the field poles. If we apply the rule given above we find it gives an identical result.

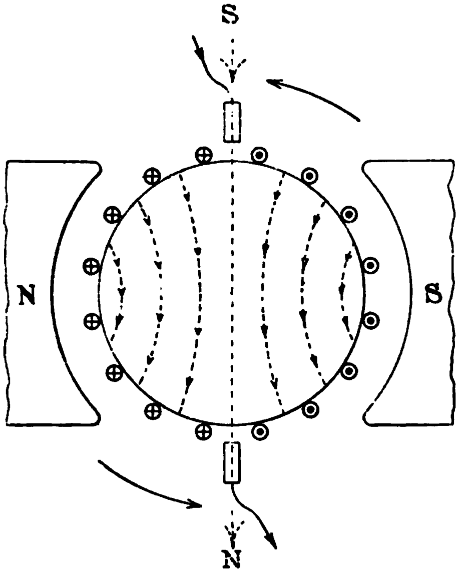


FIG. 577.—DIAGRAM SHOWING MAGNETIC POLARITY OF A MOTOR ARMATURE.

The magnitude of the total force on a conductor depends upon three things: (1) the length of the conductor lying at right angles to the field and to the direction of the force; (2) the current strength; (3) the flux density. The numerical relation is simple, and follows from the C.G.S. system of units, and what has been said on page 238 regarding unit current. For if there is a force between the conductor and the unit pole it must be a mutual one, *i.e.* action and reaction are equal and opposite. Hence a centimetre of conductor carrying unit current in a field such as there is at one centimetre from a unit pole, experiences a force of one dyne. The field at such a position is one line per square centimetre.

---

* The recommendation is frequently made to effect this reversal by using the left hand for motors and the right for generators. In the author's opinion this is strongly to be deprecated unless for people of unfailing memory. It is far safer never to use any but the right hand, and to remember, as may be easily done, that in a motor the flow of current is opposed to the E.M.F. induced by the motion.

The force is proportional to each of the three factors given just above, so that we can now write

$$F = c \times B \times l$$

where F is the force, *c* the current strength, B the flux density, and *l* the length of conductor in centimetres perpendicular to both *c* and B. To change this from dynes and absolute units of current into kilograms and amperes we write

$$\frac{C}{10} \times B \times l \times \frac{1}{981 \times 10^{3}} = F \text{ (kilograms)},$$

B being still expressed in lines per square centimetre and *l* in centimetres. We may otherwise write

$$\frac{C \times B_{''} \times l'' \times 2{\cdot}54}{10 \times 2{\cdot}54^2 \times 981 \times 453{\cdot}6} = \text{force in pounds},$$

that is $\frac{C B_{''} l''}{1{\cdot}13 \times 10^7} = \text{force in pounds},$

A being amperes, $B_{''}$ lines per square inch, and l'' length in inches.

From this it is easy to calculate the length of active conductor required in a given field to produce any required force with a given current.

THE BACK E.M.F.

A phenomenon very familiar to those accustomed to work with motors is the falling off of the current as the motor gets up speed. When a motor is started from standstill, a resistance is always inserted in the armature circuit, and is cut out step by step. When power is first switched on, there is a rush of current in spite of the starting resistance, but as the motor speeds up, the current decreases rather rapidly, and when it has fallen sufficiently some resistance is cut out by moving the starter handle on one step. The amperemeter shows a jump again, but falls off as the speed rises; this sequence is repeated until all the resistance is cut out, and every step is accompanied by an initial rise of current, followed by a diminution greater than the rise. Moreover, if the resistance of the armature be measured from brush to brush and also the voltage across the brushes, it will be found that the current is less than would be given by the value $\frac{E}{R}$ if E is the said voltage for all running conditions, and the discrepancy becomes greater the greater the speed of the motor. It follows that there is some condition connected with the speed of the motor which affects the current strength, cutting it down as though the armature conductors had, when moving, a higher resistance than when stationary. This, indeed, was urged to be the case in the early days, till Jacobi presented the true explanation. We have seen in the preceding pages that a conductor moving in a magnetic field becomes the seat of an E.M.F., and that the E.M.F., when the movement is produced by a current supplied to the conductor in the field, is in opposition to the supplied current. Now, in a motor, the armature is wound with a conductor disposed upon it in such a way as to be capable of producing a large E.M.F. if run at full speed, and the E.M.F. is (assuming the excitation to be constant) strictly proportional to the speed. Briefly put then, the motor in revolving always generates a *back* E.M.F., *i.e.* one opposed to the applied E.M.F., and this back or generated E.M.F. is, in a shunt motor, proportional to the speed.

FACTORS OF SPEED.

If the motor could only run so fast as to give a generated E.M.F. equal to the applied E.M.F. from the mains, it would obviously cut the current down to nothing. Under those conditions the energy supplied to the armature from the mains would be also zero, an impossible state of affairs, since there must be some supply of energy to overcome the running frictions and the hysteresis and eddy currents. If we consider the armature circuit from the point of view of Ohm's law, we have

E = a forward E.M.F. supplied from the mains,
$\mathcal{E}$ = a back E.M.F., generated in the windings,

both at work simultaneously in a circuit of which

r_a = the resistance.

We have seen that $\mathcal{E}$ must be smaller than E, and we may write the current flowing as

$$C = \frac{E - \mathcal{E}}{r_a} \text{ and } C r_a = v = E - \mathcal{E},$$

v = the voltage absorbed in armature resistance. Looking at these expressions we see that the current passing through the armature is determined by the *back* E.M.F., if the applied voltage is fixed; that is to say, that if C is to have any given value, this fixes the value of v also for that armature, and since E is fixed there can be only one value for $\mathcal{E}$ which will allow the current to have the given value, and this value of $\mathcal{E}$ is $E - v$. So that with a fixed-supply voltage we can make the current what we please by merely varying $\mathcal{E}$. This, however, is all from the supply and the electrical standpoint, and we must introduce the mechanical or output conditions to arrive at a fuller explanation. Let us assume that a shunt motor has to deliver a definite output of P, horsepower, or W, watts. Further, that there are certain constant losses due to bearing friction and sundry other items which may be considered as independent of reasonably small speed variations, these we will denote by w. Other losses in the armature are due to resistance, and may be written $C^2 r_a$, C being the current *in the armature.* The power equation now will stand

$$746\,P = W = EC - C^2 r_a - w$$

or
$$C = \frac{E \pm \sqrt{E^2 - 4 r_a (W + w)}}{2 r_a}$$

where as stated above

P = output in horse power,
W = watts,
w = friction and windage,
C = current in the armature,

the negative sign usually giving the result most in accordance with working conditions. If we substitute Cv for $C^2 r_a$, we have

$$C = \frac{W + w}{\mathcal{E}}$$

which is often useful.

Having obtained the numerical solution for C from the quadratic it follows that $\mathcal{E}$ must be of that magnitude which will leave a margin, v, of difference between it, the back E.M.F., and the applied voltage. When therefore there is the load, W, to be delivered the motor must run at just such a speed that the back E.M.F. will leave an unopposed margin of the applied voltage equal to v, and this margin will operate under Ohm's law to drive a current of exactly the value C through r_a. Thus the speed of the motor is determined by the back E.M.F. required, which in turn depends on the load.

Speed is not, however, the only factor of E.M.F. with a given armature, for the field strength is of equal importance. Hence to attain a given E.M.F. a definite field strength is needed for a given speed. Here we have a means at our disposal for varying the speed of a motor, for by weakening the field strength a higher speed is needed to produce the requisite back E.M.F. (on a given load) and the motor will run faster. Thus with a shunt motor speed regulation is easy, provided the machine is designed with a strong enough field to run at the slowest speed wanted. Resistance can then be inserted in the shunt circuit to make the machine run faster, the limit in this direction being reached when the brushes begin to spark, provided such a speed is not too high for mechanical reasons, which would impose an earlier limit. The actual apparatus used for effecting such speed regulation of motors is described in Chapter II., Section VIII. The field of a series motor may be regulated by shunting the field windings so that only a portion of the armature current flows through the field coils. The limits in this case are similar to those of a shunt motor. For speed and torque relations the reader is referred to the following pages under the heading of " Motor Characterististics."

DISTRIBUTION OF POWER IN A MOTOR.

It is of great importance to comprehend clearly the way in which power delivered to the terminals of a motor becomes transformed into various shapes and is dissipated in various directions. For the present we will continue, as in the preceding paragraphs, to ignore the energy absorbed in the field windings, seeing that this is so easily understood and determined as a heat loss due to copper resistance, and will confine our attention to the armature.

Before taking up matters of detail it is well to refer again to a broad principle already enunciated on page 200 and referred to on page 5. There is one case of a current flowing *against* an E.M.F. in which the work done appears directly in the form of heat, namely when there is a thermo-electric E.M.F. present and the phenomenon called the Peltier effect occurs. Apart from this one exception, however, it appears to be broadly true that *when a current flows against an E.M.F. the energy is transformed from the electrical " shape " to some shape other than heat. When current flows with an E.M.F., energy is transformed into heat direct.*

We should clearly understand that the energy is constantly changing its " shape " in any series of operations. For example, one shape of energy is the *relationship* existing between a fuel and oxygen ; another shape is the *condition* of vapour under pressure ; another the kinetic energy of a moving body, and yet another, heat. Hence energy may be transformed from the shape first mentioned into heat, and thence into steam under pressure, and thence into a flywheel ; in all practical cases the transformation takes place partly into some shape other than that desired, and this energy so misdirected is spoken of as lost, while that transformed as desired is usually merely described as " transformed."

Examples of the principle stated above in italics may be found in (1) the chemical changes in a lead accumulator during charge. The energy represented by the *back E.M.F.* multiplied by the current (and by time also, of course) is all transformed from an electrical into chemical shape and may be retransformed on discharge ; (2) the magnetic effect of self induction where (*see* page 200) the *back E.M.F.* of self-induction gives a product with current and time, representing the energy transformed from an electrical into a magnetic shape.

In a motor armature, the current multiplied by the *back E.M.F.* represents power transformed directly into a mechanical shape.

The total power supplied is EC, and this is separable at once into two portions Cv and $C\mathcal{E}$. Without suggesting that in physical reality there is any priority of time, we may take the power Cv and consider it first so as to dispose of it. This item is not associated with a *back E.M.F.* but only with a forward one, and comes under the latter part of the broad statement opposite. The magnitude of the E.M.F. really associated with this transformation is v, and the energy passes at once into heat to the extent given by the familiar expression C^2rt and commonly called copper loss (*see also* page 242). The remaining item of power is $C\mathcal{E}$, and this undergoes *direct* transformation into mechanical shape. It does so by virtue of the force on the conductors in the field and the velocity of their movement in the field, it being a simple and interesting exercise in the application of fundamental units to establish the connection between watts and horse power on this basis. The power here may be regarded as both transformed in shape and transmitted direct without loss to the conductors, which in turn transmit it to the armature core. The connection is not so obvious in the case of modern toothed armatures as in the old smooth-core machines. It may be seen to hold if it be remembered that the action on the armature teeth is due to the magnetic polarity which they possess in virtue of the current in the conductors. The power so delivered to the armature core does not, however, all emerge in mechanical shape at the pulley or coupling. The armature, even though uncoupled or not belted, demands power to revolve it at normal speed, the power demanded being made up of the following items (*a*) hysteresis; (*b*) eddy currents; (*c*) windage; (*d*) bearing and commutator friction. It is not unusual for the student to content himself in regard to items (*a*) and (*b*) by saying vaguely (though correctly) that both occasion heating, and therefore demand power. It is, however, quite easy to be precise and understand how each makes its demand for torque and hence for power, since the machine is running at a definite speed. With reference to hysteresis, all the while some one piece of armature iron is under a pole face there is no tangential force due to mere polarity, but the moment it passes from the region of uniform field to a position under or beyond the pole-tip, the persistence of polarity (hysteresis) in the armature iron occasions a tangential backward pull towards the pole face it is leaving, and force has to be applied to tear it away from that pole. If the polarity persists until the region of influence of the succeeding pole is felt, force will be needed to urge the polarised piece of iron towards the pole of same sign. In generators and motors alike therefore there is this definite force needed, supplied in the generator through the shaft and lost as a deduction before energy can be imparted to the conductors, but in the motor it is supplied to the conductors from the outside source and lost after transformation to a mechanical shape, so forming a deduction of the energy that shall reach the shaft.

The case with eddy currents is similar. They only occur in portions of the core subject to a changing field, and at instants when the change is occurring. A reference to page 234 will show that there is a pull between the conductor (iron), carrying the eddies, and the field producing them where a separating movement is in progress; while there is repulsion where an approaching movement is found. These forces of attraction and repulsion make their demand on the energy delivered to the core by the conductors (motor) and form a second deduction. The third and fourth deductions are now readily understood as mechanical torques also, and the mechanical power transformed direct from $C\mathcal{E}$ in the conductors, only emerges at the pulley or coupling, shorn, so to speak, of the items (*a*), (*b*), (*c*) and (*d*).

EFFICIENCY.

The efficiency of the transmission from the conductors to the pulley depends therefore upon the magnitude of the above items, while the efficiency between the terminals and the conductors is dependent upon the magnitude of the C^2r loss, or copper loss, as it is usually called. The efficiency between terminals and pulley therefore includes all these losses, and further also the losses in the field magnets. These last have not been specifically referred to. They are copper losses and consist of the heat dissipated by the resistance of the shunt or series winding, or both, as the case may be. The heating of the pole tips by eddy currents may be taken account of by considering the reaction of these eddy currents on the armature core, and so included in item (*b*), for the loss really occurs in the transmission between armature conductors and pulley. Of all the losses involved the only important variable is the copper drop in conductors carrying the main current, *i.e.* in the armature conductors and in any series windings. The other losses' remain sensibly constant if the speed be constant, excepting the eddy current losses in the pole faces. These last vary greatly with, and are due to the armature current; at the same time they are at their maximum value small, compared with the other losses, and may be disregarded for the present.

Apart from the constant losses, therefore, the efficiency depends only on the copper losses being higher as these become less. The transformed energy being $\mathcal{E}$C the efficiency (still considered apart from the constant losses) would be

$$\eta = \frac{\mathcal{E}\,C}{E\,C} = \frac{E - v}{E}$$

but $v = Cr$, where r is the resistance of the armature, and any winding in series with it. Hence the efficiency will be 100 per cent. when the value of r is zero and only then. Otherwise it depends on the value of $\frac{\mathcal{E}}{E}$.

This result is interesting as showing how the efficiency of a motor depends upon the speed, for in a given field $\mathcal{E}$ is directly proportional to the speed.

Modern machines are usually constructed with very high flux densities as compared with those of, say, fifteen years ago, and the losses included under "constant losses" above are by no means negligible in comparison with the copper losses, even at full load. The efficiency therefore can only be properly considered by paying regard to the quantity w at all loads.

OUTPUT LIMITS.

The limit to the output of a machine run at a given speed is to be found either in the heat developed by the losses or in the sparking, whether the machine be motor or generator. It is both instructive and interesting to note the progress of design from the days of the Pacinotti toothed core and the Gramme ring. With the constants then employed for design (such few as there were) the sparking limit was very soon reached with the Pacinotti machines, so much so that they were discarded and entirely superseded by smooth cores. Even then it was the sparking limit which determined the output for many years. Attention to commutation and brush gear led to improvements by which the sparking limit was pushed further and further until, in the early 'nineties, quite excellent commutation was obtained even when machines were loaded until they ran as hot as could be allowed, and so the heating limit became the determining factor for output. Even then a fixed brush position from no-load to full-load was an unattained desideratum, and attention appears to have been devoted almost exclusively to this for some years. Then came a further extension of the heat limit by the introduction of better ventilated cores, and the cooler conditions of multipolar as compared with bipolar construction, although multipolar designs were used by Professor Kapp at least, and possibly others, somewhere about 1890. To meet the demand on the commutation excellence created by the extension of the heating limit, carbon brushes received more concentrated attention, finally enabling the much-desired return to be made to toothed core designs. These in their turn entirely ousted the smooth core from the field, and at the same time the heating was still further reduced by fan-blade pulleys, ventilated field coils, and open commutator spiders, while armature ventilating ducts were multiplied and enlarged and core spiders built as open as possible. Thus the heating limit again overstepped the sparking limit until another return to an almost forgotten feature of design, namely, the use of interpoles, has now, seemingly, placed the sparking limit far ahead of anything that we may ever hope to reach with the heating limit.

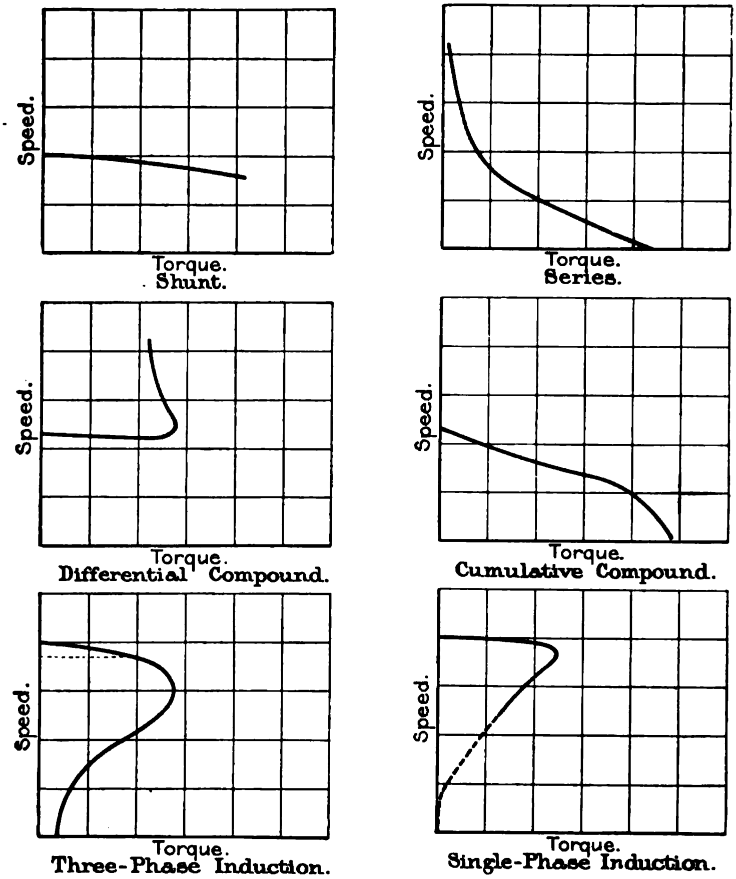
The net result of these stages of progress, coupled with the great improvements in the permeability and hysteretic qualities of the magnetic materials used, is that the dimensions of, say, a six-pole 100-kilowatt machine of 1895 would suffice to-day for a 250-kilowatt machine at the same speed. The efficiencies, however, have not progressed in the same way, for it must be clear that the improved ventilation only means improved dissipation of, not a reduction of, the internal losses of the machine.

It may be pointed out in this connection that the output of a machine in kilowatts is a function of the speed, and that with every increase of speed an increase of power is obtainable up to a point which is well beyond practical conditions. With increase of speed, however, comes an increase of the iron losses, while the copper losses remain constant; hence the effect on the efficiency can only be stated when the ratio of copper to iron losses is known at some given speed. It will be obvious also that with a given machine, running at a given speed, the output for intermittent loading will be greater than for continuous loading if the same heating limit is imposed. Such intermittent loading occurs with crane motors, tramway motors, etc., and the rating of such machines, *i.e.* the horse-power at a given speed without overheating, is much higher than with machines for continuous loading only.

The construction of machines, chiefly motors, for operation in damp, or very dusty places or even in the presence of corrosive or inflammable gases, has led to a general classification of machines into "totally enclosed," "ventilated," "protected," and "open" types. The first of these is least favourably, and the last most favourably, constructed for dissipation of the heat resulting from the energy lost, so that, output for output, the totally enclosed machine is much larger and more expensive than the open type for the same speed; but on the other hand a 20 horse-power crane motor which is intermittently loaded is much smaller and cheaper to buy than a 20 horse-power motor which would be running continuously.

MOTOR CHARACTERISTICS.

The mechanical characteristics of motors under various conditions of supply are given in Fig. 578. For the most part the curves are self-explanatory, as they represent the relations of torque and speed, as indicated in the diagram. Reference has already been made on page 488 to the compound motor and the effects of differential and cumulative winding. The shape of the torque-speed curve for the series motor is instructive, and shows the great suitability of that type of motor for starting under heavy load as in crane work and tramway work. On the other hand, the practically constant speed of the shunt motor under varying load is well shown in the curves. The characteristic of the three-phase induction motor will be seen to illustrate the changes in torque which have been described on page 572. The approximate running speed is indicated by the dotted line.



Shunt.
Series.
Differential Compound.
Cumulative Compound.
Three-Phase Induction.
Single-Phase Induction.

FIG. 578.—CURVES CONNECTING TORQUE AND SPEED FOR VARIOUS MOTORS, THE SUPPLY E.M.F. BEING CONSTANT.

THEORY OF SINGLE-PHASE MOTOR.

The operation of the single-phase motor is very interesting. It must be clear that a single-phase current can only produce a magnetic field of an alternating or oscillating character. It is true that a single-phase supply is frequently used to produce fields which are not merely alternating but are rotatory in character, but this result is only attained by the use of what is either openly or disguisedly a "phase-splitting" device. If a short-circuited coil of wire be placed in a simply alternating field it is under conditions similar to those affecting the secondary winding of a transformer. Consequently, if the field follows a sine law, being equal at any instant, t, to $N_{max} \sin 2\pi f t$, the E.M.F. induced in the coil will follow a cosine law. If we *neglect* any *self-induction* the coil may have, and assume that the current follows *the same* cosine law, the force between the field and the induced current will be proportional, at any instant, to the product of the sine and cosine of the same angle. In short we have

$$N_t = N_{max} \sin 2\pi f t,$$

$$E_t = 2\pi f N_{max} \cos 2\pi f t \text{ (per turn of coil)},$$

$$C_t = \frac{2\pi f N_{max} \cos 2\pi f t}{R},$$

and the force per unit length of conductor

$$= C_t \times N_t = \frac{2\pi f N^2_{max}}{R} \sin 2\pi f t \cos 2\pi f t.$$

The resulting force in one period will be obtained by integrating during one period. But we have already pointed out (Sec. VI. page 361) that the integral $\int_0^{2\pi} \sin\theta \cos\theta \, d\theta = 0$. So that the force turns out to be zero on the above assumption. The well-known experiments of Elihu Thomson show that in all ordinary cases there *is* a force, from which fact it is clear that our assumption is wrong, and that self-induction does *not* play a *negligible* part. If we include the effect of self-induction in our expressions, we shall have to give the current an angle of lag, say, ϕ, and the integral for the period will be of the shape

$$\int_0^{2\pi} \sin\theta \cos(\theta - \phi) \, d\theta,$$

which gives $\pi \sin\phi$ instead of 0. Self-induction is thus obviously an important factor in determining the force in such a case. The experiments of Elihu Thomson referred to, include the floating of a heavy copper ring over the pole of an alternating-current electromagnet. This is shown in Fig. 579. The forces between the currents in the ring and the alternating field are alternately attractive and repulsive, but owing to the lag of current the latter predominates and the ring is driven away from the magnet core. It is shown held down by strings. If the current were leading, instead of lagging, the attractive forces would predominate. Now in a short-circuited rotor such as is shown in Fig 558, there is not one coil only, but many, and all are subject to similar conditions. As usual (*see* page 233), we may consider individual wires or may consider them in pairs forming single-turn coils.

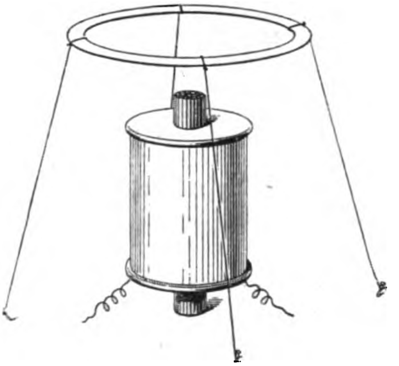


FIG. 579.—COPPER RING FLOATING ABOVE ALTERNATING CURRENT ELECTROMAGNET.

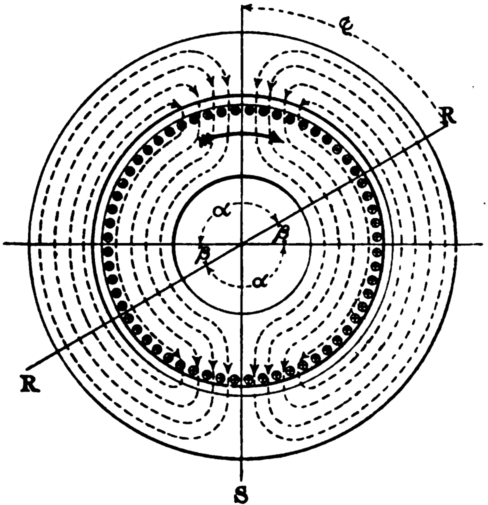


FIG. 580—DIAGRAM OF FLUX AND CURRENT RELATIONS IN SINGLE-PHASE MOTOR UNDER RUNNING CONDITIONS.

Whichever method is followed, a little reflection shows that though *each bar* (or pair of bars) experiences a definite resultant force in each period, the effects on all the bars are divisible into two sets mutually opposing and cancelling one another. Hence on the whole *rotor* there is no resultant torque.

Let us now impart some movement to the rotor (*see* Fig. 580) turning it by hand or otherwise in, say, a clockwise direction. The effect is that, owing to the lag of the currents behind the induced E.M.F.s, the bars will have moved on in the interval of time elapsing between the occurrence of maximum E.M.F. and maximum current. Maximum E.M.F. occurs at the instant of zero field, so that at the instant of maximum current the field will have some value and the magnetic axes of stator and rotor (regarded for the moment as electromagnets) will be given by such lines as S, S and R, R respectively. In a two-pole motor the angle ϕ will be the angle of lag of the rotor currents behind the rotor E.M.F.s. Moreover, if the field be growing, at the instant represented, the directions of current and field will be as shown. All the conductors in the angles α will now be subject to forces (*see* page 632) tending to produce clockwise, and those in the angles β to forces tending to counter clockwise rotation. Clearly the clockwise forces gain the day.

To start such a motor therefore, it must be rotated sufficiently fast to make the angle α exceed the angle β by an amount which will give a torque large enough to overcome friction and other internal mechanical losses. It will then accelerate itself. The rotation might have been made the reverse way by merely starting the reverse way. The torque rises to a maximum with increasing speed (*see* Fig. 578), and then decreases till at a speed a little short of synchronism it becomes zero. It is not difficult to see that the rotor currents, on account of the inclination of their magnetic axis to that of the stator, behave, in a measure, like a second winding to the stator supplied with current having a phase displacement relatively to the actual stator winding. The combined effect of the stator and rotor currents thus produces a result like that of a two-phase stator, except that the phase relation is less definite, and a rotating field of a kind is produced. The peculiar features of this field are non-uniformity of distribution and of speed of rotation. It is not possible within the scope of a work like the present to enter more fully into the theory of the single-phase induction motor, and the reader is referred to the writings of Professor Ferraris and Mr. Heyland, and to a very interesting treatment of the subject by Mr. M. B. Field.*

It must suffice to state here that these writings rely in the main upon resolving an alternating field into two rotating components revolving in opposite directions with the same frequency as that of the alternating field, and each of half its amplitude.

Further reference to the use of motors on a single-phase supply will be made in a later chapter.

DESIGN TESTING.

Of late years the testing of electric machinery of all kinds has grown to be a very important branch of electrical engineering, and all large firms have a special department equipped with a large and varied assortment of modern machines and instruments in order to obtain really accurate tests on every class of work turned out by them. There are two distinct classes of tests which the testing staff is called upon to make: first, tests on new or altered types of machines, and, second, tests on machines of standard types. The second class is made to find out if the particular machines come up to a certain specified standard fixed for that type and size of machine, and does not require to be made with the fulness and accuracy demanded by the first class, which is made with a view to finding out the properties of a new design.

---

* *Electrical Review*, 1899, Vol. 44, pages 194, 271, 439, 492, 579.

As stated above the designer is now enabled to work at much higher electric and magnetic densities than formerly.

Yet, although the weight of copper and iron used must be reduced as much as possible to keep down prime cost, the constant losses must also be kept down to give good efficiencies, and, to make the total constant losses a minimum, it has been found that the component items must bear to one another a ratio lying between fairly definite limits. These limits, though known approximately for various types of machines, will vary with numerous variations in the design, mechanical as well as electrical, and consequently the only method of obtaining ultimately the best machine is to carry out exhaustive tests, and to alter the design to eliminate the defects as discovered by those tests. The rapid development of electric driving of all kinds has led to the construction of machines which still further complicate designing and make testing still more necessary, as they are required to possess a number of opposing qualities. This is especially the case with motors of the totally enclosed type, such as the dust-proof, water-tight, or gas-tight motors for use on tram-cars, in sawmills, chemical works or coal mines; for these must in many cases be placed in positions where very little space is available, so that the designer has to exercise considerable ingenuity to produce an unventilated motor to go into the limited space and to give the required power without overheating. Naturally, the testing of machines where so little latitude is allowed is extremely important, for the designer should know all that can be known about the behaviour of his machine when working under all probable conditions of running, as a very slight difference in the proportions may make all the difference between an efficient motor and a troublesome one. We will deal in the present chapter with those tests which are made only or partially for the benefit of the designer, and in the following chapters with the works testing of standardised types.

ARMATURE AND BRUSH RESISTANCE.

The simplest method of measuring armature resistance is to pass a current through the winding, measure the current and the drop in voltage, and calculate the resistance by means of Ohm's law. This method is applicable to almost all sizes of machine, and results of high accuracy may be obtained with resistances as low even as 0·0001 ohm by using a standard moving coil ammeter and millivoltmeter. The current employed should be derived if possible from an accumulator, and be of such value as to give not less than 20 millivolts drop. The contact resistance between the voltmeter leads and commutator is the chief source of error. A current is passed through the armature, care being taken to see that the latter is clamped and the leads of a millivoltmeter are placed, if small currents are used, on the segments under the middle of two adjacent sets of brushes if the machine is lap wound. A better method is to make a punch mark in the end of the segment with a fine prick punch, and to place the well-cleaned points of the voltmeter leads in the marks, as this practically eliminates contact resistance. If the winding is of the wave form it is necessary to find out the segments which complete one circuit and to use them. It is as well to lift all the other sets of brushes off the commutator and so to get the resistance of one circuit, the resistance of the armature being obtained by dividing this resistance by the number of circuits in parallel. As there may be some slight variation in the resistance of the different circuits through the armature, it is advisable after the reading has been taken, to lift the two sets of brushes which have been in use and let down another pair, taking the resistance of the circuit they complete, and so on until the resistances of all the circuits have been taken. The average of these measurements divided by the number of circuits in parallel will represent the resistance of the armature. The current used should be as large as possible, preferably the full load current in one armature circuit.

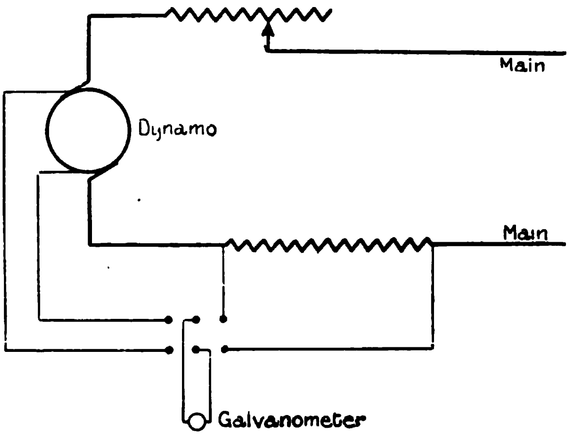


FIG. 581.—MEASUREMENT OF ARMATURE RESISTANCE BY COMPARISON WITH A STANDARD.

Another method, useful in the case of small machines, is by comparison with a standard. As before the armature is clamped and a current passed through it, and also through two resistances in series with it, one being variable, and the other fixed and of a definite known value. From a galvanometer leads are taken through switches to the ends of the known resistance, and to the armature whose resistance is required, and since the same current flows through both, the fall of potential through the armature and that along the resistance are proportional to the respective resistances, and the readings of the galvanometer are proportional to the falls of potential. Fig. 581 is a diagram of connections. After the first deflection has been obtained and the second compared with it, the first should be checked again at once to see whether there is any variation of current or resistance, and the tests repeated if necessary until steady, concordant results are obtained.

A third method, and one which can be very rapidly and accurately carried out down to values of the order of 0·001 ohm, is by the use of the potentiometer, for a description of which *see* page 342.

The resistance of the largest armatures is as a rule very small, and may be obtained by a method which obviates the use of excessively heavy currents such as would be needed by those just described. The best method is by means of the Thomson bridge, of which Fig. 582 is a diagram of connections

A = armature
R_1 R_2 R_3 R_4 = variable resistances
R = standard low resistance
G = galvanometer
K K_1 = keys
B = battery

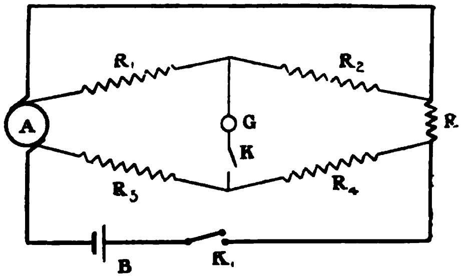


FIG. 582.—MEASUREMENT OF ARMATURE RESISTANCE BY THOMSON BRIDGE.

R_1 and R_3 should be as nearly equal as possible, and so should R_2 and R_4. If R_1

and R_3, or R_2 and R_4, are not equal, then $\frac{R_1}{R_3}$ must equal $\frac{R_2}{R_4}$. R_1 and R_2 are varied until no current flows through the galvanometer when the key is depressed. When balance is obtained $\frac{A}{R} = \frac{R_1}{R_2}$.

This equation is obtained as follows—

As in the case of the Wheatstone bridge:

$$\frac{A + R_1}{R_3} = \frac{R + R_2}{R_4}$$

$$\therefore A = \frac{(R + R_2) R_3}{R_4} - R_1$$

$$= \frac{R R_3}{R_4} + \frac{R_2 R_3}{R_4} - R_1$$

Now we have already said that $\frac{R_1}{R_3}$ must equal $\frac{R_2}{R_4}$ $\therefore R_1 = \frac{R_2 R_3}{R_4}$

Substituting above we get

$$A = \frac{R R_3}{R_4} + \frac{R_2 R_3}{R_4} - \frac{R_2 R_3}{R_4}$$

$$= \frac{R R_3}{R_4} = \frac{R R_1}{R_2}.$$

In this method the resistance of the leads has no appreciable effect, and consequently the actual test may be carried out in the test bed office or other room which is more convenient for galvanometer working than the open test bed.

BRUSH CONTACTS.

The next operation is to obtain the contact resistance of the brushes. By making contact with the galvanometer wires to the brushes as close down to the commutator as possible we can get the combined armature and contact resistance, and on subtracting the armature resistance we have the contact resistance as difference. Similarly by connecting the wires to the tops of the brushes and to the terminals successively, we may obtain the brush resistance and resistance of the brush leads respectively.

If readings are taken for various strengths of current passing from brush to commutator, it will be found that the contact resistance varies considerably, decreasing as the current increases, in such a way that the voltage drop across the contact is roughly constant at all loads. The pressure of the brush on the commutator has also a considerable effect on the contact resistance, the resistance decreasing with increased pressure, as would be expected. Care must be taken, however, not to increase the pressure beyond a certain limit, which is usually from 1½ to 1¾ lbs. per square inch, though it is sometimes as high as 2 lbs. If the pressure is increased to a higher value than this, the increase of heat loss due to increased brush friction more than counterbalances the reduction due to decreased contact resistance. The speed of the commutator also affects contact resistance, but to such a small extent that it is taken account of only in academic investigations.

FIELD RESISTANCE.

The resistance of a series field winding being very small is measured by the same methods as are used in obtaining the armature resistance. As, however, shunt windings have a comparatively large resistance, those methods are used which have been described already under the measurement of resistance. The usual and simplest is the one first described under armature resistance, in which an ammeter and a voltmeter are used.

SPEED MEASUREMENT.

In all efficiency tests the measurement of speed is of the greatest importance, and in motor tests, of course, of equal importance with that of the torque. There are two common methods of measuring speed, one being by means of a revolution counter and a watch, and the other by means of a tachometer. Both methods are open to objection on the score of introducing additional friction at the bearings when the pointed end of the spindle, belonging either to tachometer or speed counter, is pressed into the end of the motor spindle. At heavy loads or with reasonably large machines this additional friction is doubtless negligible, but considerable pressure may be needed to prevent slip if the tip of the tachometer spindle is somewhat worn, and hence at light loads quite an appreciable additional power is demanded from the machine to drive the speed measuring apparatus. Of the two classes of instruments the tachometer is undoubtedly the more satisfactory for several reasons. In the first place the speed is indicated directly, and as it is quite easy to see from the behaviour of the pointer whether slip is taking place or not, the pressure never need exceed the requisite amount. On the other hand, it is impossible to see whether the speed counter is slipping, although one can generally feel whether it is or not, and hence, as a rule, speed counters are applied with greater force than need be, just in order to make sure that they do not slip. With a little practice, however, speed counters may be reliably used without undue pressure, and of course they possess the merit of great cheapness, costing about one-fifteenth to one-twentieth as much as a reliable tachometer. A further advantage inherent to the tachometer is that when the load is varying, or the conditions of the supply are at all variable, the reading can be practically instantaneous, so that simultaneous readings can be taken of speed, torque, and power supplied at any instant that happens to be propitious. With the speed counter it is necessary to take a reading of at least one half minute's duration, and preferably of one minute. Undoubtedly the most satisfactory tachometer is a fixed tachometer driven from a pulley on the motor spindle ; but this, of course, is an expensive piece of apparatus, and involves fixing to the machine shaft a pulley of the right diameter.

In addition to the above simple methods of measuring speed, there are three others which are not quite so simple. One of these, due to Professor Fleming, consists of a small centrifugal pump, drawing water up a graduated glass tube, the height at which the water stands depending on the speed at which the pump is run. The tube can be calibrated to read directly in revolutions per minute. This method has the disadvantage that it absorbs a certain amount of power. The second method is an electrical one. A small dynamo, with a permanent magnet which has been artificially aged, is connected directly to a voltmeter. Assuming that the strength of the magnet is constant, and that the voltmeter takes a negligible current, the voltage will be exactly proportional to the speed at which the dynamo is driven. The voltmeter can therefore be calibrated to read direct in revolutions per minute, or if for use in railway motor tests, in miles per hour. The third method is something like the second, except that a small permanent magnet alternator is substituted for the dynamo, and a frequency meter for the voltmeter. The frequency is, of course, directly proportional to the speed of the alternator, so that the frequency meter can also be calibrated in revolutions per minute. This last method has been developed by Messrs. Johnson and Phillips.

SEPARATION OF LOSSES.

It has been shown on page 644 how to obtain the resistance of the field, armature, brush, brush contacts and field windings, and consequently the loss due to each of these at any load may easily be found. These are usually designated as the "copper losses." There are, further, the losses due to eddy currents, hysteresis, friction and windage. The method most frequently adopted for separating these in the case of continuous-current machines, is that of Kapp and Housman, in which it is assumed that hysteresis and friction vary directly as the speed of the armature, and that the eddy current loss is proportional to the square of the speed, the excitation being kept constant. Therefore the first operation is to separate the losses into two parts, one proportional directly to the speed, and the other to the square of the speed.

The machine is, therefore, separately excited with normal full load excitation, and run light as a motor with various voltages on the armature, which consequently runs at various speeds, since the speed is under these conditions proportional to the voltage applied to the terminals. The current required at the various voltages is measured, and a curve plotted with armature current as ordinates, and volts as abscissæ.

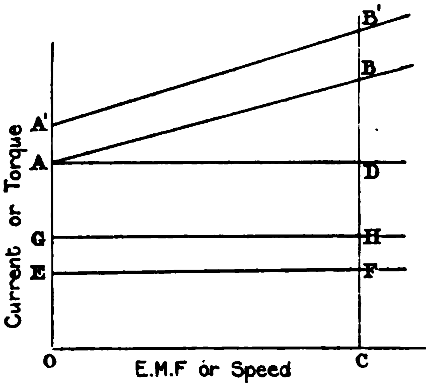


FIG. 583.—SEPARATION OF LOSSES IN ARMATURE.

The result should be a straight line as A B in Fig. 583, cutting the current axis above the origin. The total no load loss at any speed, say C, is the product of the co-ordinates of B, *i.e.* O C × C B.

On drawing a horizontal line through A to cut C B at D, the area representing total loss is divided into two parts, the one, O D, being proportional to O C, and the other, A D × D B, being proportional to the square of O C, since B D is proportional to A D and therefore to O C. Hence the first area represents the loss due to hysteresis and friction, and the second that due to eddy currents. It should be particularly noted that it is the *product* of the co-ordinates of the point B which represents the loss, and not the area of the figure A O C B.

As the hysteresis loss cannot be conveniently determined, the machine is coupled direct to another machine, and driven unexcited by the latter, first with the brushes lifted and then with them down in position, the power necessary in both cases being observed. This will be found to be practically independent of speed.

These results are added to the diagram as the lines E F and G H, and the remainder of the loss below A D, namely the area G D, is therefore the loss due to hysteresis.

Other sets of readings may be taken with different values of field, and plotted in curves such as A′ B′; these curves are, except for abnormally high field densities, when the eddy currents in the armature and pole tips produce demagnetisation, parallel to A B, and A′ B′ will be above or below A B, according as the new field density has increased or diminished the total losses.

The losses due to hysteresis increase with an increased field, while, owing to the decrease in speed required to generate a given voltage if a higher field strength is used, those due to friction decrease, and there will, therefore, be a certain value of the field strength which will bring the loss curve into the lowest position, and it is this position of minimum loss that designers endeavour to attain. Further refinements in the separation of losses are occasionally required, in which case an amplification of this method, as described by Mr. Housman on page 641, Vol. XXXI., of the *Journal of the Institution of Electrical Engineers*, will be found useful.

Dr. Sumpner has devised a method, in development of that introduced by M. Routin, of testing alternators and other machines having heavy revolving parts which is eminently suitable for works testing, as the only apparatus required is a watch, a good tachometer, and a method of applying a small retarding torque.

The machine is run up to a speed, R_1, as a motor, and then the supply cut off and the machine allowed to drop to a speed, R_2, about 10 per cent lower.

The time taken in slowing down must be accurately observed by counting the ticks of a watch. Although rather difficult at first, yet after some practice this method gives far more accurate results than could be obtained by the use of a stop watch.

The loss of kinetic energy by the rotor in slowing down is

$$a\,(R_1^2 - R_2^2)$$

where a is a constant depending on the moment of inertia of the rotor.

If T is the retarding torque due to losses in the machine, T varies very slowly with the speed and may be regarded as constant during a change of 10 per cent. If T is constant R diminishes uniformly, so that the work done in the interval t, while changing from R_1 to R_2, is

$$T \times 2\pi n \times t \text{ or } 2\pi T \times \frac{R_1+R_2}{2} \times t$$

$$\therefore \pi T t \times (R_1+R_2) = a(R_1^2 - R_2^2)$$

$$Tt = \frac{a}{\pi}(R_1 - R_2)$$

Again, let the speed drop from R_1 to R_2, but this time under an additional measured torque T′. The time t' taken to accomplish the change in speed will be proportionately less and

$$\frac{T}{T'} = \frac{t'}{t-t'}$$

$$\therefore T = T'\frac{t'}{t-t'}$$

$$\therefore Tt = T'\frac{tt'}{t-t'} = \frac{a}{\pi}(R_1 - R_2)$$

On solving this equation we obtain the value of a and can then arrive at the work, $T \times 2\pi n \times t$, done during the change, and so at the horse power required to maintain the average speed.

This experiment should be carried out (1) without excitation, and with brushes lifted; (2) without excitation but with brushes in place; (3) with excitation and brushes lifted. Then we get the loss due to (1) bearing friction and windage; (2) bearing and brush friction and windage; (3) bearing friction, windage, hysteresis and eddy currents, and are so able to separate the various losses. Further, by varying the average speed the variation of the losses due to speed may be studied. The measurable torque T′ may be applied by means of a brake in the well known way.

TEMPERATURE.

One of the most important points about a machine is the temperature rise of its various parts above the temperature of the surrounding air, after a proper continuous run on full load. The maximum temperature attained should not be great enough to be detrimental to the value of the insulating material, either by softening, decomposing or carbonising. As also continual variations of temperature undoubtedly impair its insulating value, and wide variations more rapidly than smaller ones, it is advisable to keep the temperature rise as low as possible. It is conceivable, further, that chafing occurs from the expansion and contraction of metal parts, by which the insulation is exposed to wear and abrasion, which may be appreciable with very large ranges of temperature change.

As cotton is the material nearly always used for insulating both field and armature, temperature is an especially important matter, since cotton becomes charred at comparatively low temperatures, and when that has occurred, the machine is liable to break down at any moment. In this connection the investigation carried out by Mr. Rayner at the National Physical Laboratory for the Engineering Standards Committee is very valuable. He found that there was no serious alteration in cotton up to about 125° C., that it then commenced to blacken, and that at 180° C. it became nearly black and very brittle. Even in this state it was an excellent insulator compared with cotton at atmospheric temperature, there being practically no leakage, and on a high voltage being applied it stood almost as much as at any other temperature. But there is another point which must be taken into account, and that is, that insulation even if not noticeably charred, may be so deteriorated that it fails mechanically owing to the vibration set up in the conductors due to the attraction between field and armature, or even by the chafing above referred to.

Consequently most engineers agree that it is unwise to allow any cotton-covered conductors, even though varnished, to attain a greater temperature than 100° C.

The American Standards Committee have taken 25° C. as the standard air temperature ; but, of course, some engine rooms, especially in summer, may rise considerably above this, and as a margin must also be allowed for possible overloads, it is recognised that the maximum temperature rise should be about 50° or 60° C., giving an actual temperature of from 75° C. to 90° C. ; but the practice varies, as will be explained later.

Before any temperature readings are taken, the machine under test should be run for such a length of time that it has attained a steady temperature, that is, heat is being generated and radiated at the same rate. Any observations made before this steady temperature has been reached, as to temperature, sparking, overload capacity, losses or regulation, are quite useless.

To ensure that a steady temperature has been reached, machines are run on full load for a certain time which varies with the size of machine, its type, duty and the custom of its maker. The Standardisation Report of the American Institute of Electrical Engineers recommends that a run of from six to eighteen hours, according to size and construction, be given to machines for continuous working, and one hour continuous run to machines for intermittent working. Having made sure that the maximum temperature has been reached by all parts, the machine is shut down and the temperature of armature iron and copper, field windings, and commutator taken.

In works this is generally effected by placing thermometers, having very narrow bulbs, into intimate contact with the parts, and covering the bulb with a small pad of cotton wool or waste, so that as little heat as possible shall be lost, and the maximum reading reached as quickly as possible. Whenever any temperature is taken, the temperature of the air in several places in the neighbourhood of the machine should also be noted, for it is not the temperature of the parts that we require, but the temperature rise of those parts. In the case of the armature, care should be taken to place the thermometers, one on the teeth and the other on the winding, as near the middle of the armature as possible, as that is the place which gets the smallest amount of ventilation, and is therefore hottest. The field thermometers should be placed underneath the tape if the magnets are taped, or held close against the wire, and covered with a cotton pad if the magnets are untaped, one thermometer being placed on the outside of the coil, and another between the coil and pole if there is sufficient room. On a compound machine the temperatures of both coils are taken.

Another method of measuring temperature is by means of change of resistance. The resistances of armature and field coils are taken when the machine is cold by the methods already described, and again after it has attained a steady temperature. Then, as copper has a temperature coefficient of 0·0042 per degree Centigrade at ordinary temperatures,

$$R_t = R_o\,(1 + 0{\cdot}0042t)$$

where R_t = resistance at temperature "t."
R_o = resistance at 0° C.

Unless with a modern accurate millivoltmeter, or a modern form of potentiometer, this method is not considered advisable for large armatures, as on account of their exceedingly low resistance a very small error in observation, in conjunction with the low temperature coefficient of copper, may lead to a comparatively large percentage error, which may quite well give a difference in the double reading of from 10° C. to 15° C.

It should be borne in mind that the temperature obtained by one of these methods is not comparable with that taken by the other, for while in the latter case the result is the average temperature of the winding, that in the former is the temperature of the hottest part of the outermost and therefore coolest coil, and is as a rule considerably below the average, while both differ considerably from the temperature which determines the breaking down effect on the insulation, that is, from the maximum temperature in any part of the winding. This latter is very difficult to obtain ; in fact as a rule it is only in experimental machines of radically new design that it is required, and in these cases it is obtained by thermo couples or resistance wires, usually the latter, embedded in various parts of the winding.

It has been found in practice that if the temperature as taken in either of the above two ways does not exceed certain limits, the maximum temperature at any part will be within the value permissible for the insulation. The American Standardisation Report recommends the values given below above a room temperature of 25° C. If the room temperature is not 25° C. an allowance of ½ per cent. per degree should be made for each degree above or below this, deducting the allowance if the temperature is above 25° C., and adding if below.

Field and armature ...	By resistance 50° C. rise.
Commutator and slip rings	By thermometer 55° C.
Squirrel cage and short circuited armatures	By thermometer 55° C.
Apparatus for intermittent service except railway motors	By resistance 50° C.
Railway motors with covers removed	By thermometer 75° C.

In this country the British Engineering Standards Committee have not at the time of going to press issued their recommendations, but in their interim report they state that, if the results of experiments already carried out are confirmed, they will in all probability be able to recommend a higher temperature rise than has yet been considered safe by similar committees in other countries.

As, however, it is usual in ordinary workshop testing to take field and armature temperature by thermometer and not by resistance, the allowable rise must be less than 50° C.

Different makers naturally hold different opinions, and many allow different rises in different types of machine, but it will be found that the variations in the practice of well-known firms are, as a rule, small and unimportant.

Most firms make no difference between the parts, and merely specify that no machine is to show a higher temperature rise (taken by thermometer) in any part, than 40° C. or 70° F., although some allow 45° C. or 80° to 85° F. on alternating-current machines, and a few also allow a higher rise in the case of semi-enclosed, or totally enclosed machines.

In the case of the first few machines of a type, cooling curves are also plotted by taking a series of observations of the temperature of the parts at regular intervals during the cooling period. Plotting temperatures as ordinates, and times as abscissæ, curves are obtained which can be extended back to cut the ordinate line at time 0, thus giving the exact temperature when the load was taken off. These curves are kept for reference and the results obtained in future tests compared with them to see that there is no appreciable variation from the standard.

THE TESTING OF IRON

It is of very great importance to the dynamo builder to know what are the magnetic qualities of the iron or steel that he uses for those parts of his machines which must carry magnetic flux. As a rule, quite a rough test, instituting a comparison between the materials supplied and some standard piece of old material which the dynamo builder retains for reference, will suffice for his needs. But should an entirely new brand of iron be brought out, it is of great interest and often of importance to be able to make an exhaustive series of tests upon the material, with a view to finding out, not only the relation between B and H, but also the hysteresis loss and the electrical resistance. This latter quantity may prove significant as a guide to the amount of eddy current loss in the new brand as compared with what would be obtained in former brands.

ROWLAND'S METHOD.

One of the earliest methods and one of the best, although tedious, is Rowland's method of testing iron. A sample of the iron to be tested must be made up in the form of a ring, which is then overwound with a coil of wire, as shown at S in Fig. 584. The object of making up the sample in the shape of a ring is that the magnetic circuit is then complete, and the whole of the magnetomotive force applied is expended in driving lines through iron of the quality to be tested. A perfectly steady source of current is employed to send current through the magnetising coil, and, of course, for this purpose a battery of accumulators is the best thing. Between the battery and the magnetising coil are inserted a reversing switch S_1, an adjustable resistance R, and an ampere meter A. A second coil S_2 is also wound over a short length of the iron ring and is connected to a ballistic galvanometer B G through what is known as an earth coil E C. This last piece of apparatus consists merely of a coil containing a great number of turns, and usually of fairly large diameter, preferably something of the order of 20 centimetres (8 inches). The following data must be accurately known in order to make the test :—

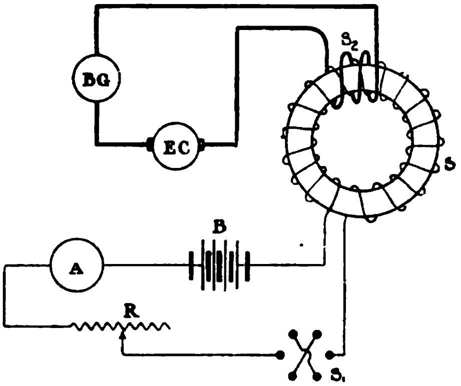


FIG. 584.—ROWLAND'S METHOD OF MEASURING PERMEABILITY.

Firstly, the inside and outside diameters or the mean circumference of the sample ring.

Secondly, the mean cross-sectional area of the sample ring.

Thirdly, the number of turns in the magnetising coil.

Fourthly, the number of turns in the search coil.

Fifthly, the mean diameter of the earth coil and the number of turns in it ; and

Sixthly, the value of V, the vertical component of the earth's field at the place where the test is carried out. If this value V be not known, then either the horizontal component and the angle of dip must be known, or the total force and the angle of dip.

If there is uncertainty or difficulty in the use of the earth's field, if, for example, it cannot be accurately known, or if it is liable to considerable interference from neighbouring machinery or moving masses of iron, it will be better to dispense with the earth coil and to replace it with a standard solenoid (*see* page 314). The amperemeter should be very carefully calibrated just before use, and the galvanometer must be truly ballistic, preferably one whose logarithmic decrement has been measured (*see* page 313). In making the test, the current in the magnetising coil is first adjusted to a very low value such as will give an H of 1 or perhaps 2, the galvanometer being short circuited the while. The reversing switch is then thrown over and back again several times in order to eliminate, as far as can be, the residual effect in the iron of having been magnetised in one direction. This operation also renders the iron " mobile " and ready to respond to a definite magnetising force. The switch after these rapid reversals is left on, the amperemeter reading carefully and rapidly observed, the galvanometer circuit opened, and the switch thrown over so as to reverse the current. All these operations are performed in succession as rapidly as can be. The instant the reversing switch is thrown over the galvanometer is deflected and the spot of light makes an excursion across the scale. The furthest point of the first swing must be carefully noted and the galvanometer may then be short circuited in order to bring it to rest. As soon as the galvanometer is at rest the short-circuit plug should again be removed and the earth coil which is lying flat on the table should be rapidly turned over by hand so that the face which was uppermost is now lying on the table. This will again deflect the galvanometer, and, as before, the first swing should be read. The galvanometer is then short circuited, the current in the magnetising coil readjusted to a slightly greater value, and the whole series of operations above described is then repeated. The throw of the earth coil need not be taken every time, but it should be taken at fairly frequent intervals, particularly if the galvanometer be of the Thompson four-coil type ; it is of less importance to take it frequently if the galvanometer be of the D'Arsonval type, as this type of galvanometer is not subject to nor controlled by external fields and is only likely to change its constant with temperature changes.

The principles upon which the test depends are, firstly, that the throw of the galvanometer is proportional to the quantity of electricity which has passed through it ; secondly, that the quantity of electricity sent through a circuit of given resistance in a given time is proportional to the time integral of the E.M.F. applied ; and thirdly, that the time integral of the E.M.F. set up by cutting a definite number of lines of force is independent of the rate at which they are cut. The test really compares, by means of the ballistic galvanometer, the time integral of the E.M.F. set up in the search coil by the reversal of the flux in the sample ring with that of the E.M.F. in the earth coil due to reversing through it the vertical component of the earth's field. The average value of the E.M.F. set up in the search coil is equal to $\frac{2Ns}{t}$ while that in the earth coil is $\frac{2VSA}{t_1}$ where

N is the flux in the ring,

s the number of turns in the search coil,
S the number of turns in the earth coil,
A the mean area of the earth coil.

The quantity of electricity displaced in the circuit is the average current multiplied by the time, hence:

$$Q = C \times t = \frac{2Ns}{t \times R} \times t$$

if R is the resistance of the circuit.

Therefore $$Q = \frac{2Ns}{R}$$

for the search coil and

$$Q = \frac{2VSA}{R}$$

for the earth coil.

The total number of lines cut by each turn of the search coil is clearly 2N, since the field is not only wiped out but reversed, and the same, of course, applies to the presence of the factor 2 in connection with the E.M.F. set up in the earth coil. Incidentally these expressions also show that the total energy generated by cutting a given magnetic field by a circuit of given resistance is independent of the rate of cutting; that is to say, it is of fixed value for that field and that circuit, no matter whether the lines be cut rapidly or slowly. This method of testing iron has two disadvantages, the one being that it is exceedingly tedious, and the other that it demands considerable skill on the part of the experimenter if he is to obtain really accurate results. At the same time it is, perhaps, the only method which is capable of giving really accurate results. The results obtained, however, give no information concerning the hysteretic qualities of the iron, and in point of fact, do but give a mean value for the permeability. The earth coil provides an exceedingly convenient way of bringing the galvanometer to rest, the galvanometer being readily controlled by its aid, so as to bring it to rest at the end of two swings, whereas short circuiting it will often not bring it to rest in less than five or six swings. In place of Rowland's ring it would be quite permissible to employ a bar; the objection, however, to the employment of a bar is that a correction has to be applied in calculating the results to allow for the effects of the two ends. The ends of a magnetised bar may be regarded as exerting a demagnetising effect on the whole; but these effects may be reduced to a very small value by employing bars whose length is very great in relation to their diameter, say one hundred times or more, the whole length of the bar being wound with the magnetising coil and the search coil being placed in the centre of the bar. The employment of a bar gets over the difficulty of having to make up the sample in the form of the endless ring above mentioned.

HOPKINSON'S METHOD.

Dr. Hopkinson in 1885 described a method employing samples made up in the form of pairs of rods of circular section. The samples must be turned exactly to size, in order to pass through holes in the ends of a large block of annealed wrought iron in the shape of a long hollow rectangle. One end of each sample rod is truly faced, so that when these two ends are brought together there is good magnetic contact. One rod is clamped so as to be immediately in the hole through one end of the block, and the other rod has a loop secured to it by which it can be pulled through the hole. The exciting coil is made in two halves, each half being wound on a bobbin, which is received in the rectangular space enclosed by the block; one sample rod is then thrust through the hole and fixed so that its faced end does not quite protrude through the bobbin into the space between the two. The search coil is then slipped into this space and the other test rod pushed through the opposite hole and the other half of the exciting coil, until its faced end comes into contact with the first test rod. The exciting coil is connected to a steady source of current through an amperemeter and adjustable resistance as in Rowland's arrangement, and the search coil is connected to the ballistic galvanometer also in the same way as before. In applying the test a weak current is first turned on, the short-circuit plug of the galvanometer is removed, and the movable test bar is suddenly pulled out, thus releasing the search coil, which is snatched out from its position between the two exciting bobbins by an indiarubber spring. The search coil thus cuts the whole of the lines of force which before were threading it, and gives a throw on the ballistic galvanometer. The coil is then replaced and held in position while the movable test bar is replaced; the current is then slightly increased, and a fresh throw taken, and these observations are continued for various exciting currents until the iron is thoroughly saturated. A falling curve is then taken, the current being gradually reduced by small amounts, or it can be raised to its maximum value each time the test bar is inserted, and then reduced by successively greater amounts before pulling the test bar out, thus giving accurate results for the falling curve. This method, therefore, has the great advantage over Rowland's of giving us data concerning the hysteresis in the iron. It has the disadvantage of requiring the test bars to be accurately turned to the required diameter, and what is more undesirable, it requires one end of each to be accurately faced, a matter demanding time and occasioning expense. In order to eliminate the error due to the magnetising force required to magnetise the yoke the latter is made of very large section as compared with the test bar. It will be seen that only half the flux traversing the test bars is carried by each side of the block, and this block is given a sectional area about one thousand times as great as that of the test bar.

BIDWELL'S METHOD.

This method consists of an application of Maxwell's law of traction (*see* page 210). To apply it, the sample to be tested is made up in the form of two half rings, the two ends of each half are carefully faced so that when the two half rings are put together a practically continuous circular magnetic path is provided. One half is wound with a magnetising coil and the other is provided with a hook to which weights or a spring balance may be attached. The weight of the half ring must also be known. The wound half is then attached to some fixed support, so that the line adjoining its two faced ends is horizontal. A magnetising current is turned on and the other half ring brought into position, where it is held by the magnetic attraction at its two ends. Gradually increasing weights, or a gradually increasing force by means of a spring balance, is then applied until the lower half ring is detached from the upper. The force necessary to detach it is carefully noted, and the value of B is calculated from the expression given on page 210. It must be remembered that the total force of attraction to be overcome is made up of two presumably equal ones, one acting across each pair of faces.

The magnetising force is, of course, readily obtained by counting the number of turns in the exciting coil and the current flowing, and this force is expended over the whole ring.

Bidwell has also employed bars instead of rings, the bars being similar to those employed by Hopkinson, but the test consisted in measuring the force necessary to pull the bar apart instead of measuring the throw on a ballistic galvanometer as in Hopkinson's method.

S. P. THOMPSON'S PERMEAMETER.

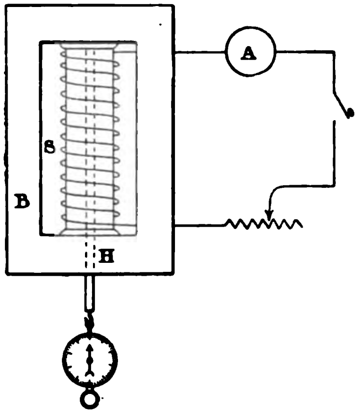


FIG. 585.—PROF. S. P. THOMPSON'S PERMEAMETER.

Dr. S. P. Thompson has devised an exceedingly convenient apparatus for testing specimens of iron. By its aid tests can be carried out exceedingly rapidly, and they do not demand special skill. The permeameter consists of a large block (Fig. 585) of wrought iron not unlike that employed by Hopkinson. An exciting coil S wound upon a brass bobbin, is placed in the rectangular space enclosed by the block. The sample may be made up in a rod of any section, provided it is not too large to pass through the hole H drilled in one end of the block B. The thickness or diameter of the section should preferably be such that it just passes freely through the hole H. One end of the specimen is carefully faced and butts up against the iron at one end of the rectangular space. When current is turned on Maxwell's law of traction gives the force by which the faced end is held on to the iron block, and the force to detach it is then measured by a spring balance. As the core only is moved and the coil remains stationary, the pull in this particular case is not that due to B lines per square centimetre, but to B—H.

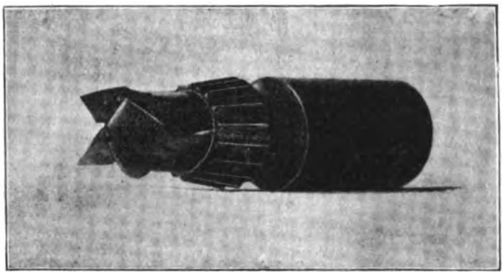


FIG. 586.—DRILL FOR DRYSDALE'S PERMEAMETER.

This method is very suitable for rapid workshop tests, giving a comparison between samples of new brands or new stock and a piece of old standard material which may be always carefully kept for reference and comparison.

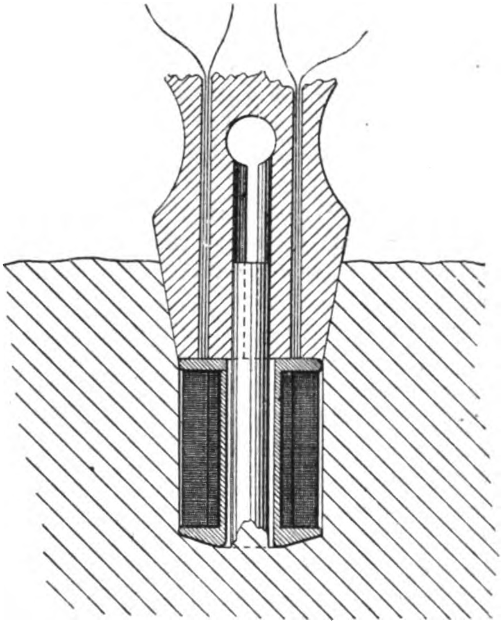


FIG. 587.—SECTION OF PLUG OF DRYSDALE'S PERMEAMETER.

MAGNETOMETER METHOD.

The magnetometer method is about the least useful of all, since it is exceedingly difficult to deduce from it any information as to the actual value of B in the iron to be tested, and further because the sample must be a piece of rather unusual shape. The method consists in subjecting the sample to the action of a magnetising coil, and observing the deflection produced upon a magnetometer placed in the neighbourhood of one of the poles. In order to obtain satisfactory results, the sample should consist of a rod whose length is not less than one hundred times its diameter, and hence a brand of iron to be tested must be made up into a somewhat awkwardly shaped sample before the magnetometer method can be applied. If, however, a standard sample for comparison is kept, the method gives exceedingly accurate results for hysteresis as well as for permeability, but it must be remembered that a magnetometer cannot be used conveniently or with satisfaction anywhere in the neighbourhood either of large masses of iron subject to displacement, or dynamo machines, or of wires carrying currents of any magnitude. It becomes, therefore, essentially a laboratory method, and in this respect is in strong contrast to the permeameter above described.

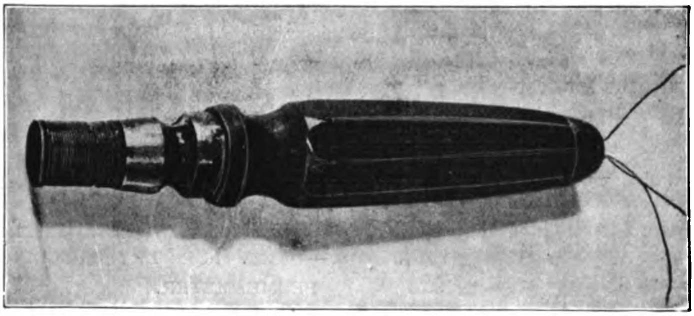


FIG. 588.—PLUG OF DRYSDALE'S PERMEAMETER.

DRYSDALE'S PERMEAMETER.

This type of instrument has been designed by Dr. Drysdale to meet the demand for a reliable permeameter which should be able to test any sample, of whatever shape, should not require skilled operation, should be strong, capable of making rapid tests, portable, and not dependent on any standard bar of material for comparison. The method which is employed is as follows:—In the piece of iron whose magnetic qualities it is required to test, a taper hole is drilled by means of a special hollow drill (*see* Fig. 586), which leaves a pin of the metal projecting up the middle of the hole, as shown in Fig. 587. Into this hole is inserted a plug, the upper part of which is made of soft iron, and has a hole in it which exactly fits the projecting pin in the test piece. The plug is taper, and makes a good magnetic joint with the sides of the taper hole. The lower end of the plug carries a bobbin on which are two windings, one a magnetising coil, and the other a search coil. Fig. 588 shows a photograph

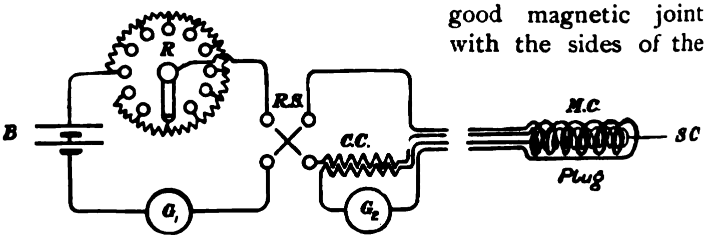


FIG. 589.—CIRCUITS OF DRYSDALE'S PERMEAMETER.

of the plug, and Fig. 587, a section showing its construction. The diameter of the hole is $\frac{3}{8}$ in. and its depth $\frac{5}{8}$ in., the diameter of the pin being $\frac{1}{10}$ in. The whole apparatus forms a permeameter of the test rod and yoke pattern, the projecting pin being the test rod, and the yoke being formed partly by the plug and partly by the external mass of the test piece. The measurements are made in the ordinary way, by reversing the current in the exciting coil and noting the throw on the ballistic galvanometer to which the search coil is connected. Fig. 589, shows the connections employed.

B is the battery supplying the exciting coil M C through the variable resistance R, the ammeter G_1, and the reversing switch R S. G_2 is a ballistic galvanometer connected to the search coil S C.

The ammeter G_1, for use with an exciting coil with a given number of turns and a test pin of given length, can be calibrated to read in H, and the ballistic galvanometer, for use under similar standard conditions can be made to read directly in values of B. This, of course, much reduces the time required in testing. The instrument can also be used to plot the hysteretic loop, and thus give an indication of the quality of the iron as regards losses.

EWING'S HYSTERESIS METER.

A simple but fairly efficient hysteresis tester has been devised by Professor Ewing This is shown in Fig. 590, and consists of a permanent magnet of the horseshoe type balanced on a knife edge and free to turn about a horizontal axis, one pole being directly above the other as shown. To the magnet is attached a long pointer, which moves over the scale shown at the top of the instrument. Between the poles of the magnet, and mounted upon an axle which is capable of fairly rapid rotation, is placed the specimen to be tested. This is made up of a number of laminations in order to reduce, as much as possible the eddy current losses. Each lamination is about 3 in. long and $\frac{5}{8}$ in. wide, and are clamped together. When rotated in the field due to the magnet, a torque is exerted on it due to the hysteresis loss, and the magnet deflects by a small amount, which is indicated by the pointer on the scale. The deflection given by a standard specimen, of which the hysteresis loss is accurately known, is compared with that obtained with the test sample, and thus the loss is immediately arrived at.

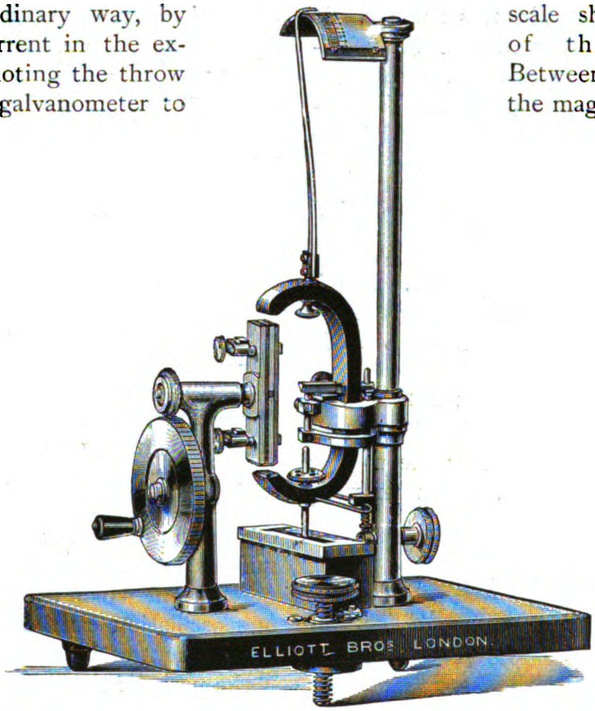

ELLIOTT BROS LONDON.

FIG. 590.—EWING'S HYSTERESIS METER.

A disadvantage is that the loss can only be obtained at one flux density.

DETERMINATION OF THE VERTICAL COMPONENT OF THE EARTH'S MAGNETIC FIELD.

Reference has been made several times to V, the vertical component of the earth's magnetic field, and it is therefore only fitting that a description of its absolute measurement should be included in this chapter. It will first be necessary to measure the horizontal component, H, of the earth's field, and from this and the angle of dip to calculate the vertical component. For if θ = the angle of the dip, then $V = H \tan \theta$.

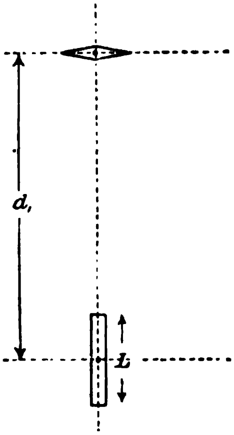


FIG. 591.—GAUSS'S END-ON POSITION.

GAUSS'S METHOD OF DETERMINING H.

A small compass needle is adjusted to swing freely, and allowed to come to rest in the magnetic meridian. A bar magnet, of length L, is now approached to the compass needle, the axis of the magnet being at right angles to the magnetic meridian, and the centre of the magnet at a distance d_1 from the centre of the needle, as shown in Fig. 591.

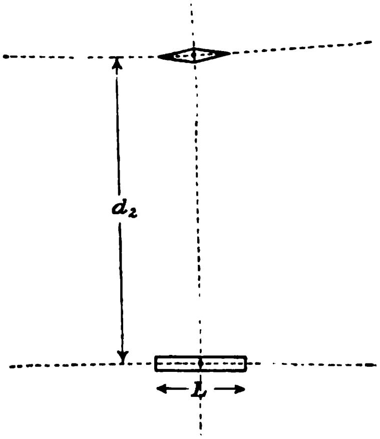


FIG. 592.—GAUSS'S BROADSIDE-ON POSITION.

The needle is, of course, deflected from its normal position by an angle δ_1. Now turn the magnet through a right angle so that its axis lies in the magnetic meridian, as in Fig. 592. Again note the deflection δ_2. In the first case, it can be shown that if M is the magnetic moment of the magnet

$$\frac{M}{H} = \frac{\left(d_1{}^2 - \frac{L^2}{4}\right)}{2d} \tan \delta_1 = \text{say } X,$$

and in the second case

$$\frac{M}{H} = \left(d_2{}^2 - \frac{L^2}{4}\right)^{\frac{3}{2}} \tan \delta_2 = \text{say } Y.$$

These values of $\frac{M}{H}$ should agree, and form a check on one another.

The bar magnet is now suspended so that it can swing freely, and allowed to come to rest in the magnetic meridian, care being taken that there is no torque in the suspending fibre. The bar is now disturbed from its position of rest by means of another magnet, and the time taken to make a number of complete oscillations is noted, from which the periodic time T of one oscillation can be calculated. If I is the moment of inertia of the magnet, and T the periodic time of the swing, it can be shown that

$$M H = \frac{4 \pi^2 I}{T^2} = \text{say } Z.$$

Combining these two expressions, we have, for the first position,

$$H = \sqrt{\frac{Z}{X}}$$

for the second position,

$$H = \sqrt{\frac{Z}{Y}}$$

Having found H, it is easy to find V as shown, from $V = H \tan \theta$.

CHAPTER IX.—WORKS TESTING.

EFFICIENCY — LARGE MACHINES — ALTERNATORS — MOTORS — FRICTION BRAKES — EDDY CURRENT BRAKES—SERIES MOTORS—RAILWAY MOTORS—TRANSFORMERS.
APPENDIX: PRESSURE DROP IN ALTERNATORS—COMPOUNDING OF ALTERNATORS.

BESIDES the exhaustive tests carried out for the benefit of the designer, every manufacturer carries out a workshop test on all machines before they leave his shop or are put into stock, in order to make sure that they come up to the specified efficiency at various loads, and fulfil all the other requisite conditions, both electrical and mechanical.

On these tests there are some other important points to note. The armature must run true and without vibration, pulsation or noise, and the bearings must not heat up.

If the speed is not correct a note to that effect must be made, as it is occasionally permissible to pass a machine whose speed is not quite to standard.

As a rule the machine must run sparklessly at all loads from nothing to 50 per cent. overload without any alteration in the position of the brushes, though with some few special machines the brushes may be shifted to suit the varying load. It is extremely important to keep a close watch on the commutation of every machine, because sparking may indicate many defects not inherent in the machine, such as faulty spacing of brushes or pole tips, a wrong field coil, or an open circuit in the armature.

After a new type of machine has been thoroughly tested and standardised, the results of the exhaustive tests carried out on the first few machines are tabulated and kept for future reference in the test office.

These results are usually recorded in the form of curves, and in the subsequent testing of machines of that particular type a few points only are taken and compared with these curves, and if they agree the machine is taken as up to standard. Thus we seldom find that in routine testing, characteristic curves, brush, field or armature resistance, magnetic leakage, field distribution, separation of losses or cooling curves are required, but the results of these tests on the type should be at hand for comparison if required.

The chief shop test is that for efficiency and temperature. The efficiency of a machine should not be taken until all its parts have reached the maximum temperature they will attain under working conditions, and this of course will not be until after a run of several hours, though the actual time will vary considerably with the size of machine and its design.

The maker's test is carried out somewhat as follows:—The machine is connected up according to the particular method to be employed, and is started with the brushes in the neutral position. Load is then put on gradually, and if sparking occurs the brushes are shifted forward (with a generator) until full load is reached, when the brush position for sparkless running is marked. The machine is then run for the required length of time on full load, readings of main current and voltage, field current and voltage, and speed being taken frequently and recorded on the test sheet with the exact time when taken. These readings are usually taken every half hour, but if the run is short, as it sometimes is with very small machines, they may be taken at shorter intervals.

At the end of the run the machine is shut down and the temperature of the armature iron and copper, field windings and commutator taken and recorded every half minute until each thermometer has reached its maximum. The machine is then started up again and run for half an hour on 25 per cent. overload, shut down, and temperatures taken as before, and finally run for five minutes on 50 per cent. overload, and temperatures taken again. If sparking occurs at either of the overloads, the brushes should be rocked forward and the position of sparkless running marked as was done for full load, and the state of commutation at different loads entered on the test sheet. Then the machine is run for a few minutes at $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ load, the state of commutation being carefully noted.

During these tests a sharp look out is kept for any defects, either electrical or mechanical, such as want of balance, humming, hot bearings, etc., which if slight, are rectified after test, but if serious the machine is at once returned to the erectors. Having proved satisfactory up to this point the machine is next "flashed," that is, the dielectric strength or resistance to rupture is tested by the application of a high alternating voltage to the terminals of both field and armature. The value of this high alternating voltage varies with the terminal voltage of the machine under test, and different makers adopt different standards, but for ordinary voltages up to 500 the flashing voltage varies between 1,000 and 2,000 volts. With alternating current machinery the frequency should be that of the machine under test.

EFFICIENCY.

Efficiency tests are conducted contemporaneously with the temperature tests, as until a machine is at its maximum temperature it is impossible to obtain its true efficiency, for until then the C^2R loss is continually increasing.

LARGE MACHINES.

For large generators and motors perhaps the best known and most widely used test is Kapp's modification of the Hopkinson parallel method. This can only be used when there are two machines of the same size and type available, but in large works this is not as a rule a serious drawback. This test is so popular because the demand upon the works generating station is very small, enough current only being required to make good the losses in the two machines. It is therefore an economical method, but owing to the different excitations it is not quite accurate. This small inaccuracy is however, probably more than balanced by the ease and precision with which the few observations necessary can be taken. It is usual to supply the loss electrically, but if this is not convenient it may be done mechanically, though this interferes somewhat with the great simplicity of the method.

The two machines are connected together mechanically, and are then connected in parallel to the shop mains in such a manner that the voltage at the terminals is the rated voltage of the machines. If possible the machines should be direct - coupled; if connected by belt an allowance must be made for the loss of efficiency due to the belt.

Both machines being connected in

parallel to the shop mains, they would work as motors if started up.

As one is required to generate it must be driven by the other, so the field of the latter must be weakened, and consequently a resistance R is inserted in the field, making it run faster; at the increased speed the other acts as generator. Fig. 593 shows the connections: F_1 and F_2 being the fields of the motor and generator respectively, R a variable resistance in series with the motor field, S a starter, and A_1, A_2 and A_3 ammeters.

Both machines are started as motors, the resistance R being cut out. As soon as the machines are up to speed, R is gradually inserted, the field is weakened, the speed increased and the motor therefore assists, by means of the mechanical coupling, in driving the other machine. As the resistance is cut in the motor takes more and more load, first assisting the other machine and so reducing the current it takes, then driving it entirely without assistance, and finally the second machine begins to generate, and continues until it is giving full load current. This current together with a small current from the mains to make good the losses of both machines is taken by the motor. The efficiency of the combined set is clearly

$$\frac{EC_g}{EC_m}=\frac{C_g}{C_g+C_l}$$

where C_g = current from generator,
C_m = current to motor,
C_l = current from line.

And assuming the efficiencies of the machines to be equal then the efficiency of one machine $=\sqrt{\frac{C_g}{C_g+C_l}}$

In this case no account has been taken of the field currents, but these can easily be added to the current in the respective machines. To obtain the best results the rated full load current of the machines should be midway between the current taken by the motor and that given by the generator.

BY TESTED MACHINES.

All works have a number of machines for testing purposes which have themselves been very thoroughly tested both as generators and as motors, and their efficiencies at all loads and speeds recorded. Consequently they can be used for testing either motors or generators, and are usually coupled to the machine to be tested by means of a belt. A great advantage of this method is that both the input and the output are electrical, and can therefore be quickly and accurately measured. If a generator is to be tested the shop machine is run off the shop mains as a motor and drives the generator at the right speed, this being attained either by means of pulleys of the correct ratio, or by altering the motor resistances. The resistance in the generator circuit is then adjusted until it is delivering the correct current at the proper voltage to the shop mains. The machines are next run at full load long enough to allow them to attain a steady temperature, and the electrical input and output of the set are measured at ¼, ½, ¾, 1, 1¼ and 1½ load, the speed of course being taken as well. The total efficiency of the set can easily be calculated, and on dividing by the known

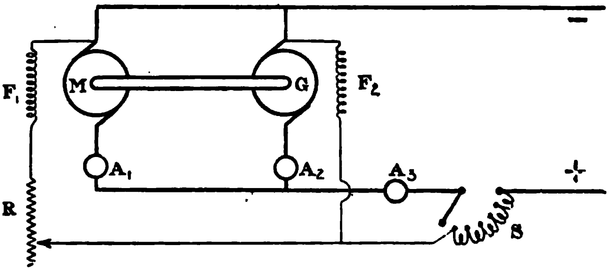


FIG. 593.—CONNECTIONS FOR KAPP'S TEST.

efficiency of the motor and by the assumed efficiency of the belt, the efficiency of the generator on test is obtained.

BY ESTIMATING LOSSES.

With a generator this method consists in estimating the various losses and obtaining the mechanical input by adding the losses to the electrical output, and thus obtaining the efficiency. It is only used for very accurate work, such as the calibration of the shop machines used in the last test.

The separation of these losses has already been described.

ALTERNATOR TESTING.

Alternators have two characteristics, the open and the short circuit, and both are taken for all machines, as is not done in the case of direct-current machines. The open-circuit characteristic, or no-load magnetisation curve as it is sometimes called, is obtained by observing field current, terminal E.M.F., and speed, and as the voltage is directly proportional to speed, each reading is corrected for the ordinary running speed of the machine, and these corrected E.M.F.s plotted as ordinates against the field current or ampere turns. As, on account of hysteresis, the ascending and descending curves do not correspond, it is most important that the field current should be gradually increased when taking the ascending curve, and gradually decreased when taking the descending. If by accident the current is raised somewhat above the value which was intended, it should on no account be reduced, but readings taken at that value, for if reduced there would be a magnetic flux, due to hysteresis, over and above the flux due to the lower value of ampere turns. As with the magnetisation curves of direct-current machines, this curve is straight at first, because with small exciting currents and low values of flux density the permeability of the magnetic path alters very little. Also the less the total reluctance of the magnetic path the steeper will be this first portion of the curve. As the flux density increases the iron comes nearer to saturation, and so a given increase in current will not produce a corresponding increase in flux, and consequently the curve bends over, the E.M.F. being proportional to flux, as the speed is constant. Fig. 607 shows the no-load characteristic of an alternator.

To obtain the short-circuit characteristic the machine is run up to normal speed without excitation, the armature being short-circuited through an ammeter. The exciting circuit is then closed through a large resistance and an ammeter, and field and armature currents noted. The field current is gradually increased, and for each value of it the corresponding armature current is noted. A curve is plotted with armature current as ordinates against field current. The short-circuit current may be increased to three or four times the normal full-load current of the machine, provided that it is maintained only for a short time. In accurate testing, readings should be taken with the field current both increasing and decreasing, as there will be a difference on account of hysteresis. With a polyphase machine all phases must of course be short circuited simultaneously.

Efficiency.—Frequently alternators are tested when coupled to the prime mover, and in these cases the efficiency of the combined set is obtained, the input being obtained from the indicator cards of the engine and the output from the wattmeter readings of the load circuit. The load is usually a water resistance, which generally gives a power factor of nearly unity, though it often exhibits a considerable capacity effect which must not be overlooked; but with polyphase machines a test on an inductive load is often taken as well.

When the alternator has to be tested separately the direct method is seldom adopted, except in the case of small machines, on account of the difficulty of measuring the mechanical input. Small alternators can be treated in the same manner as small direct-current generators, that is, by running them either direct or belt-coupled, by means of a motor of known efficiency, the alternator being loaded on a water resistance.

With large alternators it is usual to calculate the efficiency, after measuring the various losses, by dividing an assumed output by the output plus losses. If various outputs are taken a curve of efficiency may be obtained.

The excitation losses can be readily obtained from the current and resistance of the windings, as can also the armature copper loss. The iron and friction losses may be obtained in various ways.* The alternator may be run as a synchronous motor. It is run up to speed and switched on to the supply, the resistance of the field being at the same time adjusted, so that the current flowing is the least that can be used if the speed is to be maintained. The power taken is read, and represents the losses due to friction, hysteresis and eddy currents, plus the small C^2R loss due to the current in the armature. If required a correction may be made for this latter, but as a rule it may be neglected.

It may be assumed, without any appreciable error, that the friction and iron losses are constant at set loads, so a fair curve may be obtained by adding these losses to the calculated copper losses already found.

If the alternator is run on open circuit at normal speed and with its field unexcited, using a motor of known efficiency, the power required will be the amount of the friction loss. When the field is normally excited the increase in power required to maintain the speed will give the iron losses.

Mordey and Behrend.—When a single alternator has to run on a heat test there is naturally considerable difficulty both in measuring the mechanical input, and in making arrangements to absorb the electrical output. As a rule the alternator generates current at such a voltage that it is impossible to take it into the shop circuit, and so it has to be dissipated in a resistance, which, besides being unhandy, is extremely wasteful. To overcome this difficulty, Mr. W. M. Mordey in 1893 proposed a method by which the single machine could act both as generator and as motor. He divided the armature into two unequal portions, and coupled them so that they would work against each other. When the alternator is driven by a motor the larger portion of the armature will act as a generator delivering current to the smaller portion, which therefore acts as a motor.

The current which circulates through the armature coils is almost in quadrature with the resultant E.M.F., and is therefore a wattless current. Hence the poles formed on the armature by the armature current will in the generator section oppose the field poles, and in the motor section will assist them.

This leads to the magnetic unbalancing of the machine, as the motor fields carry more resultant flux than the generator fields.

In iron-cored armatures such as all modern machines have this is bad, since it altogether changes the hysteresis losses and eddy current losses. Moreover in modern machines the magnetic unbalancing causes such serious mechanical vibration that if tested in this manner they would soon shake themselves to pieces. As the armature of Mordey's machine did not contain iron this did not matter. It soon occurred to engineers to split the field instead of the armature into two portions, and to connect them in such a manner that opposing E.M.F.s were induced in the armature coils. This, however, was no better than the other method, for the mechanical stress consequent on the want of magnetic balance, was just as bad as before.

---

* *See also* page 647.

In 1903 Behrend described a simple method of overcoming this difficulty. He divided the field into two *equal* parts and supplied a different exciting current to each, so that the resultant field produced by the interaction of the impressed and induced fields was nearly the same for each pair of poles.

In this way the mechanical vibration was practically eliminated, and by suitable variations of the exciting currents any desired current could be made to circulate in the armature, and so the heat test could be carried out with a minimum expenditure of energy.

MOTORS.

The Kapp test and the test against a shop machine as described for generators are equally useful for testing motors, and for large sizes one of them is almost invariably used.

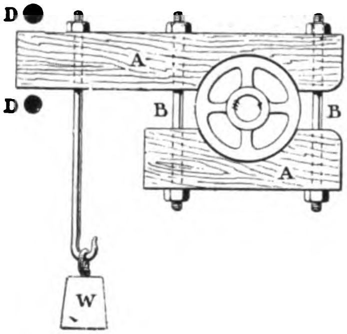


FIG. 594.—PRONY BRAKE.

For small motors, however, the various forms of brake tests are, on account of their simplicity, still much used, though all the power taken must be wasted, and not as in the other test, returned less losses to the circuit.

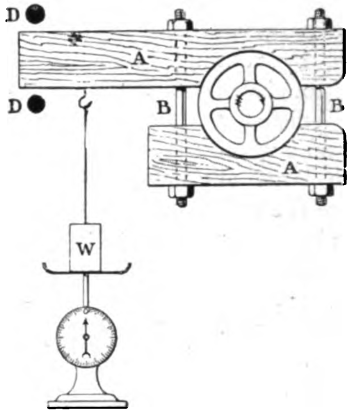


FIG. 595.—AUTHOR'S METHOD OF USING PRONY BRAKE.

The oldest and at the same time most popular form of brake is the Prony, which is illustrated in Fig. 594, and consists, as will there be seen, of a kind of clamp made of wood, which partly embraces the rim of the pulley. The clamp is composed of two blocks, A A, and the upper of these should be provided with a pipe through which soap and water can be fed to serve as a lubricant. The pressure with which the blocks grip the wheel is adjustable by means of the bolts shown at B, and the torque exerted is measured by the pull at the end of the long arm. This may be taken either by a spring balance or by a dead load of weights, and the movement of the arm should be restricted by two stops as shown at D. The author has found that an exceedingly convenient way of measuring the torque is by putting a heavy weight, which is known to be greater than that which the motor will raise at full power with the available friction, in the scale pan of a spring balance, as in Fig. 595. If a dead load is used it is difficult to adjust the grip of the brake to precisely the right amount needed to just lift the dead weight. On the other hand, if an ordinary spring balance is used there is always the weight of some part of the balance to be taken into account. The usual spring balance has a hook at one end and a ring at the other, and in order that the sliding bar may move in and out with the least amount of friction, it is usual to attach either the hook or the ring to the floor flexibly, as by a string, and the other end of the balance to the arm of the brake. The brake arm thus has to sustain the whole weight of the spring balance, though, of course, this may be taken by clamping the frame of the balance to some rigid support. The tendency of this, however, is to introduce friction in the motion of the spring and slide. Both these difficulties, as well as that of the precise adjustment needed for a dead weight, are overcome by putting a full load dead weight, or more, into the scale pan in the manner described. The only weight the arm then has to support is that of the string. Friction in the spring balance is reduced to the lowest possible amount, and any error in the perpendicularity of the string can easily be remedied during the run by slightly moving the balance in or out towards the pulley till the string is parallel with a vertical reference mark, which may be made on the wall or table supporting the motor. The method has the further advantage that at light loads the pull of the arm is counterbalanced by the difference between two forces in themselves large, viz. the downward pull of the dead weight and the upward thrust of the spring balance. Under these conditions any friction in the spring balance which cannot be eliminated is small in comparison with the other forces at work, and hence becomes practically negligible, whereas, if a spring balance alone is used and a light load is being measured, the presence of that same friction in the balance becomes important in comparison with the force at work, which is also the force being measured. When a heavy load is being measured the friction, of course, is relatively less important since the force exerted by the brake arm is itself relatively great. If the Prony brake be kept plentifully supplied with a lubricant of soap and water it will run cool and will not be very difficult of adjustment.

ROPE AND BAND BRAKES.

Nearly all motors run at what is regarded as a high speed, and the brake suitable for a pulley run at a high peripheral speed and exerting a correspondingly small torque should be different in design from the brake that has to absorb the same power, but in the shape of a large torque, at a low peripheral speed. Brakes of the latter class are required for steam engine testing. Brakes for the testing of very small motors are sometimes made of narrow webbing, with clips to prevent the webbing slipping sideways off the pulley if the latter be not provided with a convex surface; weights are then applied to one end of this band which passes over the pulley, and the other end is attached to a spring balance. The author has found that a very satisfactory brake for most purposes is that consisting of one strand, or as many more as may be necessary, of rope. There are two ways of using a plain dead weight on one side and a spring balance on the other; the one method is to make the dead weight the means by which the friction between the brake and pulley is varied, and to make the spring balance supply the force which, when

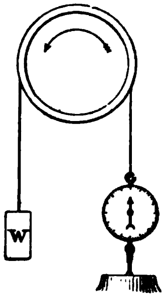


FIG. 596.—ROPE BRAKE.

the amount of the dead weight has been deducted, constitutes the load. In that case the spring balance, the dead weight, and the direction of rotation are those indicated in Fig. 596. The other method is to let a dead weight supply the forces constituting the load, and to vary the amount of friction by means of the spring balance. It is difficult to lay down any rule as to which method to use, since under certain conditions one method will prove much more satisfactory than the other, while under slightly different conditions the reverse will be the case. In general, however, the arrangement shown in Fig. 597 is that which the author has found to be most satisfactory—when the spring balance is on the tight side of the belt the greater the friction between the belt and the pulley the greater does it tend to become; hence a sort of compound interest law prevails governing the load, which therefore tends to run up suddenly or unexpectedly rather beyond the control of the experimenter. Also a very slight addition to the dead weight will sometimes cause such an increase in the power absorbed by the brake as to leave a large gap in the series of observations which it becomes difficult to fill in. On the other hand, when the dead weight provides the tighter side, the torque can never exceed a a given amount, and the only difficulty then is to provide sufficient friction to cause that torque to be exerted. Further with such an arrangement any lifting of the weight tends to decrease the friction between the brake and pulley, owing to the collapse of the spring in the spring balance. This method consequently gives as a rule much steadier running and better results, although it is sometimes a more tedious matter, and a test will therefore occupy a somewhat longer time. It is well to adopt the precaution of attaching a light line from the floor to the dead weight to check any tendency it may have to suddenly fly over the pulley.

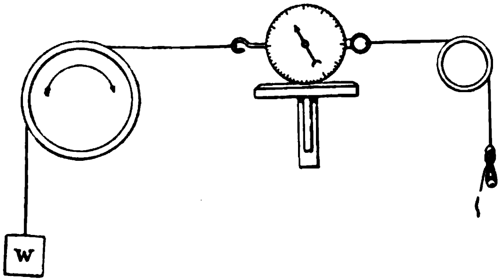


FIG. 597.—AUTHOR'S METHOD OF USING ROPE BRAKE.

EDDY CURRENT BRAKES.

When a copper disc rotates in a magnetic field eddy currents are produced in the disc in such directions as to retard the rotation, the force exerted being proportional to the speed. This is the principle underlaying the construction of all eddy current brakes. The brakes consist of two parts, first, the field magnets, and, second, the metal in which the eddy currents are to be produced. One of these revolves, being driven by the machine to be tested, and the other "floats," *i.e.* it is movable through a small angle about the same axis as the other. In some brakes such as that of Morris and Lister, described on page 668, the rotating part is a copper disc or discs, close to which are placed the poles of a multipolar field system. The induced eddy currents combine with the field to produce forces of mutual attraction between the field and discs, so that they tend to drag round the field with them, and would do so, since the field is movable, if there were not some other force supplied to counterbalance the pull. This opposing force may be applied by means of a weight capable of sliding along an arm fixed to the field system, and it is by measuring the torque exerted by this weight when adjusted so as to just hold the magnet system from revolving, that the torque exerted by the motor is arrived at. These two must obviously be equal and opposite, hence the power developed is that torque multiplied by the speed of the disc.

RIETER'S BRAKE.

This brake is an entirely self-contained apparatus which may be coupled to a motor direct or by means of a belt or other gearing; it is built in sizes up to about 60 horse-power. A diagram showing the construction is given in Fig. 598. It will be noticed that the magnet consists of only one winding encircling a core provided with the claw-like projections on both sides. All the projections on one side are of one polarity, while those on the other are of the opposite, and they are therefore arranged alternately as shown in the right hand diagram. The core of the magnet is supported on bearings by a projection from one pedestal and is the floating element, being movable through a small angle. The copper disc is in this machine replaced by a cylinder of cast iron bolted to, and supported by, a framework which is keyed to the shaft. This cylinder therefore forms the rotor and revolves, and to aid in the dissipation of the heat produced in it by the eddy currents (and hysteresis), ribs are cast in as shown. All the energy supplied to the brake, with the exception of the small amount expended in overcoming friction of the bearings and windage, is transformed into heat in the iron cylinder, and consequently a large radiating surface is required to keep the temperature down. The speed of the rotor bearing a constant ratio to that of the machine on test, if the latter be constant the brake torque is bound to be proportional only to the excitation, and so by means of finely graduated rheostats in the exciting circuit the torque can be very nicely adjusted for various loads. To the floating magnet are attached two levers both carrying weights, one a large one for coarse adjustment, and the other a smaller one to obtain the final balance.

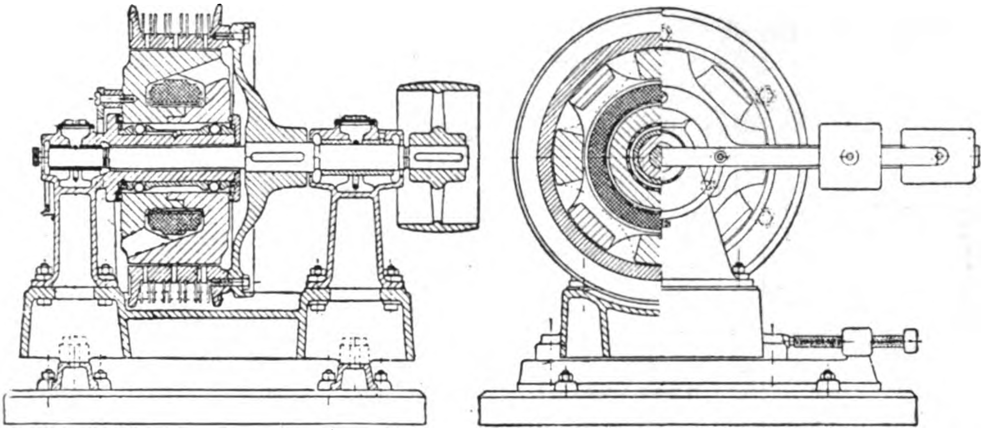


FIG. 598.—RIETER'S EDDY-CURRENT BRAKE.

Let W_1 = power expended in heat,
W_2 = power expended in friction and windage,
W = power delivered by motor,
then $W = W_1 + W_2$.

$$= \frac{\text{Torque} \times 2\pi n}{33{,}000} + W_2.$$

W_2 for any desired speed is obtained from information furnished with the brake by the makers, but it is best to find the loss at a number of speeds and plot a curve of loss and speed, and so verify the supplied data.

In computing efficiency from the results obtained by this method, an allowance must be made for the efficiency of the belt if the brake is belt driven.

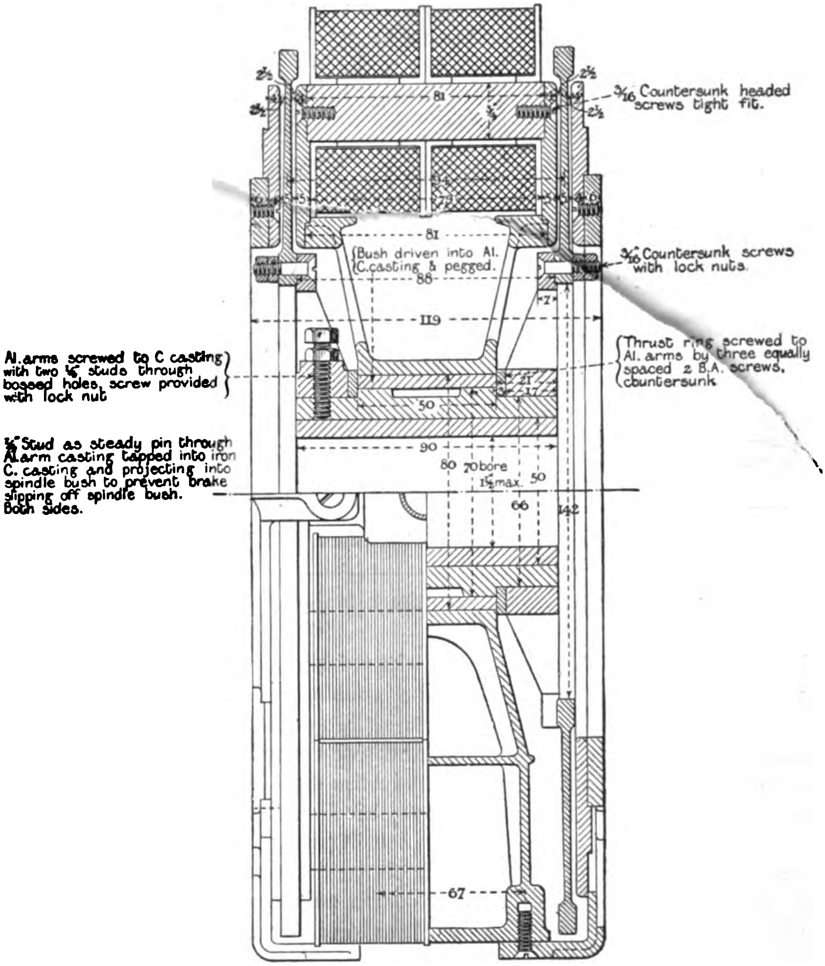

2½
2½
81
¼
2½
2½
3/16 Countersunk headed screws tight fit.
6
5
84
79
5
5
6
81
Bush driven into Al. C. casting & pegged.
88
3/16 Countersunk screws with lock nuts
7
119
Al. arms screwed to C casting with two ¼ studs through bossed holes, screw provided with lock nut
Thrust ring screwed to Al. arms by three equally spaced 2 B.A. screws, countersunk
21
17
50
⅜ Stud as steady pin through Al. arm casting tapped into iron C. casting and projecting into spindle bush to prevent brake slipping off spindle bush. Both sides.
90
80
70 bore
1½ max.
50
66
142
67

FIG. 599.—SECTION OF MORRIS AND LISTER'S EDDY-CURRENT BRAKE.

MORRIS AND LISTER BRAKE.

This brake has been designed to eliminate the correction which has to be introduced in the results obtained by other eddy-current brakes due to the friction of the bearings. This has been accomplished by making the whole apparatus so small and light for its power that it can be mounted direct on the motor shaft in place of the pulley, the weight being of less importance to the friction of the motor bearings than the pull due to a belt drive.

Fig. 599 gives a sectional view (in which some of the dimensions are in mms.) of the brake, and it will be seen that two copper discs are used, one on each side of the field coils, thus securing at the same time symmetry and double power for a given size of magnet. The discs are bolted to aluminium arms which are attached to a sleeve, and this in turn is keyed to a bush, a number of bushes being supplied with the brake and being of different internal diameter to suit various sized shafts. An aluminium spider rides on the sleeve between the discs, and carries a number of electro-magnets, the flux from which passes from one pole through the copper discs and thence to an external yoke ring, shown in the figure, and enters the next pole after having again traversed the copper discs. The yoke ring shown in the figure is fixed to the centre castings by means of brackets shown in the lower part of the figure, and in Fig. 600, which shows the finished brake; but in later designs of the brake this plan has been abandoned and the yoke ring is now fixed to, and revolves with, the copper discs. From the spider boss project the levers which carry adjustable weights and in order to improve the steadiness of the system, the weights are arranged so that their centres of gravity fall well below the levers.

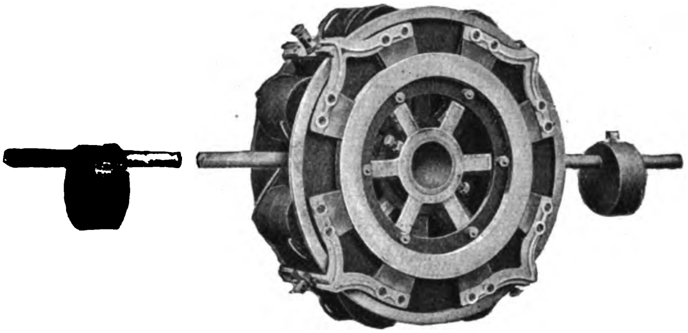


FIG. 600.—MORRIS AND LISTER BRAKE.

The error due to bearing friction is eliminated since it (the friction) merely adds to the torque and appears in the adjustment of the weights on the levers; air friction, moreover, in the early designs, is reduced to a negligible amount, so that it may be taken that the whole power given out by the machine on test is absorbed by eddy currents, and is therefore recorded by the balancing weights.

The formula for the output is consequently

$$\text{B.H.P.} = \frac{\text{Torque} \times 2\pi n}{33{,}000}$$

The brake as at first constructed was so small that it could not be used for continuous running without over-heating, but as now constructed, with fan blades for cooling purposes and specially wound coils, may be used continuously.

The windage due to the fan blades mentioned is allowed for by attaching two external guard plates to the floating brake frame, which transmit the windage torque to the brake lever.

The advantages of eddy current brakes are that they are simple in use and are extremely sensitive and accurate, no cooling by water or special lubrication is required as with other types of brakes, and the load is uniform and constant after the final temperature has been attained.

SERIES MOTORS.

Series motors form a class by themselves, since the methods of rating them are quite different from those obtaining with other classes of machines.

They are used when a very large starting torque is required, because the large flow of current at starting and when their speed is low all passes through the field coils as well as armature windings, giving a combination of intense field and heavy current in the armature, which combination results in a very large torque (*see* page 633). Their principal uses are in connection with lifts, cranes, tramways and railways, and other work where it is required to start on full load. With this kind of work the loading is usually intermittent, so the motor is frequently at rest, sometimes for quite a considerable time, and the fluctuations of current and speed almost unceasing. Since during times of light load and stoppage the motor is cooling it would be absurd to test them on a long full-load run, allowing only the usual temperature rise, and to rate them in the same manner as shunt motors and generators.

Manufacturers being aware of this, tested and rated their series motors for a long time according to their own particular fancy, the result being that the ratings were useless as a basis of comparison between the performances and prices of different makers' machines.

To overcome this difficulty the A.I.E.E. Standardisation Report recommended that "the commercial rating of a railway motor should be the brake horse-power output giving 75° C. rise of temperature, above a room temperature of 25° C. after one hour's continuous run at 500 volts terminal pressure, on a stand with the motor covers removed." This method of determining the rating has been adopted by the principal firms both in America and in this country for tramway and railway motors, while for other series motors it has been adopted down to the word "run."

Besides the ordinary heat and efficiency tests as made on all machines, temperature curves should be taken on the first few motors of a type and of a batch. To obtain one of these the motor is run on an unvarying load, and the temperature taken at intervals until a predetermined maximum is reached, say 75° C. above the air for the full load run.

This is done for various currents from ¼ to 1¾ load, and curves of time and temperature are plotted for each current.

From these curves an idea can be obtained of the temperature that will be likely to result from intermittent working under given conditions.

It is usually required to find the starting torque developed with certain currents, and this is done by means of a Prony or band brake. A weight is applied to the brake, and the circuit closed through a large variable resistance, so that only a small current flows. The resistance is gradually cut out until the motor just starts, when the current, weight and radius of action are noted. By using different weights a curve of current and torque can be obtained.

As the speed of a series motor varies greatly with current taken, a careful record must be kept of speeds during test, and curves of current and speed plotted.

RAILWAY MOTORS.

Owing to the conditions that they must be strong and yet light for their power, must be able to run sparklessly in both directions with their brushes in the neutral position, must be water-tight, must be capable of very large variations in power and speed, and must be capable of giving a high starting torque, the testing of railway motors is more exacting than the testing of most other motors. Since there are, as a rule, very many of these motors on test at one time they are tested in pairs, usually by Kapp's method or some modification of it. With the first few motors of a type great attention should be paid to the procuration of temperature curves, and speed curves in which current, brake horse-power and efficiency are plotted against speed should be taken; also performance curves in which brake horse-power, tractive effort, speed and efficiency are plotted against current. With all these curves in his possession, the designer is in a position to make accurate and useful comparisons between the capabilities of various types of motors.

After a type has been once standardised only efficiency and temperature tests are commonly taken, and the results of these are compared with the standard, and if they agree the motors are taken as correct in all particulars. Commutation is, of course, watched with the greatest care.

In addition to these shop tests some customers require further tests of the motors when in position on the car or locomotive.

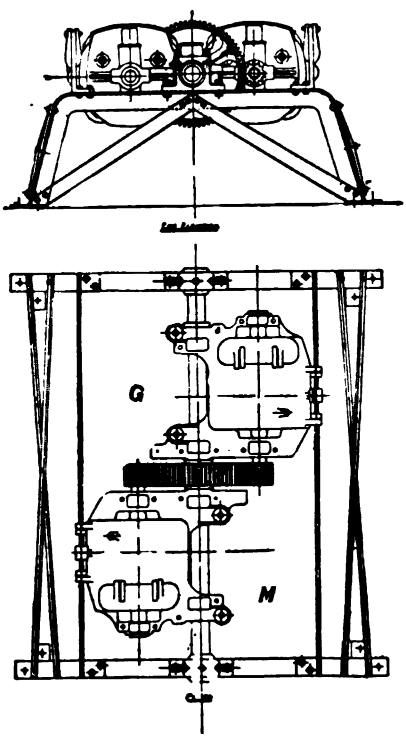


FIG. 601.—M. B. FIELD'S METHOD OF TESTING TRAMWAY MOTORS.

Some makers run their efficiency tests with the motors direct coupled, while others use a certain amount of gearing in order to more nearly approximate to service conditions. It is best, however, to work with the machines direct coupled, and so get the efficiency of the motors alone, for after all the efficiency with gearing is not of much use, as the gearing is less than is used on the car and is not worked under service conditions.

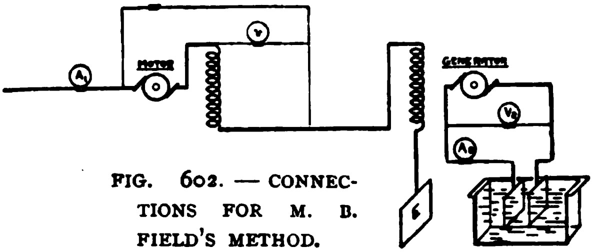


FIG. 602. — CONNECTIONS FOR M. B. FIELD'S METHOD.

FIELD'S METHOD.

Mr. M. B. Field has developed a method of testing designed to give more accurate results than those obtainable with Kapp's method.

The motors under test are erected on a frame as shown in Fig. 601, M working as a motor and G as a generator, the latter being loaded on a water resistance. The current from the shop mains after leaving M excites the field of G, so that both machines have the same excitation and run at the same speed, and will therefore have equal iron and friction losses.

Fig. 602 shows the connections.

Let R_g = resistance of generator armature,
R_m = resistance of motor armature,
r_m = resistance of motor field,
$C_1\ V_1$ = Input,
$C_2\ V_2$ = Output.
$C_1V_1 - C_2V_2$ = total loss except G field.
Ohmic losses $= C_1^2(R_m + r_m) + C_2^2R_g$.

Subtracting the ohmic losses from the total, we obtain the iron and friction losses, and dividing by two, since these losses in each machine are equal, we get the loss for one machine, and can then easily calculate the efficiency.

By means of the voltmeter, V, the resistance of the motor field can be taken with each reading of input, output, etc.; the resistance of the armature is best taken at the beginning and end of each series of tests, when if time readings be also taken, the actual resistance of the armature for any particular reading may be easily found by interpolation. By taking simultaneous readings of supply voltage, current input, speed, etc., curves may be constructed of kilowatt input and efficiency, and hence kilowatt output. Then by the aid of the speed curve tractive effort can be obtained, and also the volt-ampere characteristic for any desired speed.

With the exception of the last named all results should be reduced to a standard voltage, say 500, and a standard temperature, say 20° C.

TRANSFORMER TESTING.

The tests which should be carried out on a transformer comprise the following :

(1) Insulation test,
(2) No-load test,
(3) Short-circuit test,
(4) Resistance test,
(5) Heat test,
(6) Regulation test.

A seventh test, called the repeated switching test, is sometimes imposed.

These tests may be carried out conveniently in the order given. By placing the insulation test first, time and money may sometimes be saved, since if a transformer breaks down in the insulation test after all the others have been made, the other tests must be repeated when the transformer has been repaired. It must not be supposed, however, that all six tests must be made on every transformer that is manufactured. Nos. 1 and 2 should be made on all, but the remaining four are really design tests and need only be carried out fully on a transformer of new design.

Insulation test.—This test is threefold in character, and incidentally provides a "ratio" test.

The anti-puncture strength of the dielectric is tested from primary to earth and from primary to secondary. (The term "primary" is used throughout these tests to indicate the fine wire, and "secondary" to indicate the thick wire, winding.) For this *both* ends of the primary are simultaneously connected to one pole of the source of high pressure, the other pole being connected to the core. The secondary is carefully earthed (to core) at both poles, so as to allow the "free" induced charge in it to go to earth, and so relieve the insulation between secondary and earth of abnormal stress due to this induced charge. The test between primary and secondary is taken by applying one pole of the high pressure source to both ends of primary as before, and the other pole to both ends at once of the secondary. The testing voltage should be at least three times the normal primary voltage. Since the two windings, or one winding and core respectively, behave like two coatings of a condenser, the insulation being the dielectric, the capacity effect is quite considerable and tends very largely to cancel out any inductance in the circuit. Thus resonance of a more or less complete kind (*see* page 382) may arise, and it is well to guard against the occurrence of undue potentials by using a spark discharge gap in parallel with the high voltage leads.

Even these tests may fail to search out every part of the insulation, and it is as well to supplement them by applying to each turn of the winding about double the normal voltage in the following way: Normal voltage is applied to either primary or secondary as may be more convenient, and at this point the voltage of the other winding should be noted to see that the ratio is correct. An ammeter is placed in the supply circuit which may conveniently be a small alternator driven by a variable speed motor. Voltage is then raised to about double the normal by raising the speed of the alternator, or if this range of alteration is not permissible, part of the increase in voltage must be given by raising the exciting current. The ammeter should be watched, as it is undesirable to let the no-load current rise more than about 30 per cent. above the normal. If all the increase in voltage is obtained by augmenting the speed, the ammeter reading will not vary, owing to the rise in frequency, and the flux density will remain normal. This test is a searching one, giving double working pressure across every part of the insulation.

No-load test.—The current and watts taken by the primary when the secondary is open, and normal voltage is applied to the primary terminals must be observed. Great care should be taken to obtain normal frequency. The test may be applied equally well to the secondary winding if more convenient. The wattmeter reading is in general very low, and the instrument is working on an extremely low power factor. The voltmeter should be connected outside the wattmeter, so that its current does not pass through the wattmeter. The wattmeter reading will vary considerably with the wave-form of the E.M.F. supplied, and care must be taken that this is as closely as possible in agreement with the working conditions. It is difficult to obtain wattmeters which give reliable results under such conditions except at very high prices. Where a number of transformers can be tested in parallel this should be done, and they should be disconnected in pairs or threes so as to locate any one which may be unduly wasteful at no-load, the disconnection of such a one twice in different pairs, or three times in different threes, giving a noticeably large change in the wattmeter reading.

Short circuit test.—The secondary is short circuited through a low resistance ammeter of sufficient range to take full-load current, very heavy connections being employed to ensure a negligible resistance.

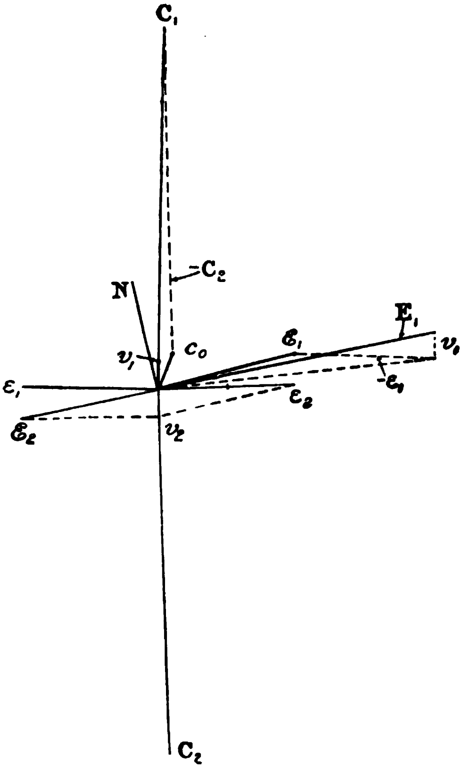


FIG. 603.—CRANK DIAGRAM FOR SHORT-CIRCUITED TRANSFORMER, ε, LEAKAGE (OR SELF-INDUCED) VOLTAGES. ALL OTHER SYMBOLS AS BEFORE. CONSTRUCT DIAGRAM AS FOLLOWS: C_2, ϵ_2, v_2, $\mathcal{E}_2$, $\mathcal{E}_1$, N, c_0, C_1, v_1, ϵ_1, E_1. $E_1 = \epsilon_1 + \epsilon_2$ VERY CLOSELY, SINCE $\mathcal{E}_2$ IS SO NEARLY EQUAL TO ϵ_2.

A wattmeter and voltmeter are inserted in the primary supply. A gradually increasing voltage, starting at zero, and of correct frequency, is applied to the primary until the amperemeter shows full-load secondary current. The voltage at the primary is approximately the sum of the voltages in the primary and secondary due to magnetic leakage. This may be understood by reference to Fig. 603, giving the vector diagram. The inscription below the diagram shows not only the meanings of the various vectors, but also the order in which they may be drawn in constructing the diagram.

The wattmeter indicates the sum of the C^2R losses in the windings, the core loss, and finally the eddy current and hysteresis losses due to the magnetic leakage. The leakage itself is, of course, no loss of power. These losses are those whose value it is desired to measure by this test, and the C^2R and core losses must be deducted from the wattmeter reading to obtain them.

Resistance test.—Resistance is measured by voltmeter and amperemeter, using continuous current. Temperature should be carefully noted.

Heat test.—The transformer is run at full load either for a specified time or until the temperature ceases to rise. Thermometer readings alone are insufficient, and readings should be taken of the primary and secondary resistances at regular intervals of a quarter of an hour at first, and half an hour towards the end. The heating test must be stopped for these readings, but by preparing suitable switching arrangements the taking of them need not occupy more than about fifteen seconds each time. When the resistance ceases to rise, particularly that of the outermost coil, the limit of heating has been reached, and the mean temperature rise may be evaluated from the resistance change. Mercury thermometers may give trouble from eddy currents in the mercury if placed in a stray field. Alcohol thermometers are free from this error and may be relied upon.

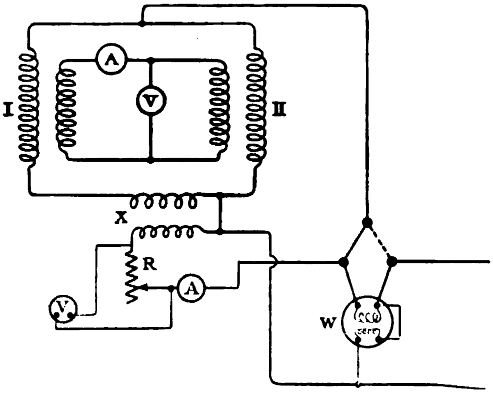


FIG 604.—CONNECTIONS FOR HEATING AND EFFICIENCY TEST FOR TRANSFORMERS.

A circulation of power method, due to Sumpner, may be employed economically where two or more transformers of the same size are to be tested. The connections are indicated in Fig. 604, and care is necessary to see that the secondaries are connected so as to oppose one another, and give full voltage and no current when the auxiliary transformer is cut out. This forms also the best method of measuring the efficiency of the transformers under full-load.

When final temperature has been reached at full-load an over-load test may be applied under any specified conditions of magnitude and duration.

Regulation test.—When the transformer is at its final temperature the secondary voltage should be measured on non-inductive load, and on inductive loads of two or more power factors, the primary supply being kept carefully at normal voltage and frequency. The differences between the secondary voltages under the above conditions and when under no-load give the "regulation" under those conditions. The regulation is expressed as the percentage which the voltage drop constitutes of the no-load voltage. A drop from 200 at no-load to 195 at full-load is called a 2½ per cent. regulation.

The results of the above tests are not difficult to handle since the losses may be easily separated if the core loss at no-load is carefully determined, and C^2R losses are separated by calculation wherever necessary.

APPENDIX.

PRESSURE REGULATION OF ALTERNATORS.

One of the most important features of an alternator, as affecting its operating qualities, is what is called its "regulation." This term is used to denote the variations in pressure at the terminals which arise from variations in the load, although the machine is run at an absolutely constant speed and with unvarying excitation. The variation at the terminals is due to two causes: (*a*) the variation in true internal lost volts due to resistance and self-induction of the armature; (*b*) the variation in the internal generated E.M.F. due to reaction of the armature currents on the field.

The excellence or otherwise of a machine in regard to pressure regulation is stated in terms of the variation expressed as a percentage of the normal voltage at the terminals, as a rise or drop. It can be expressed in one of two ways given below, of which the second is much to be preferred, viz.:—

(1) As the *rise* in voltage, which takes place when the full load is switched off.

(2) As the drop in volts, which occurs when the full load is switched on.

The test is made in each case while the speed and excitation remain unaltered. The rise in volts in the first case, expressed as a percentage of the normal voltage, is always less than the drop in volts in the second case, but the magnitude of the difference in the regulation as expressed in these ways depends very largely upon the design; for in designs where the magnetic circuit is well-saturated throughout, the rise in volts may be much smaller than the drop. The reason for this will be explained presently.

The practice is unfortunately on the increase amongst some engineers of specifying the regulation of an alternator as the rise of voltage when full inductive load is switched off.

This is done in some cases apparently because it enables the manufacturers to put in a smaller machine than if the regulation were specified as the fall in voltage when full inductive load is switched on, but it is this drop in voltage which is of practical importance.

The drop in an alternator when load is switched on is due to the following causes:—

(1) The C R drop in the armature winding, which causes a drop proportional to the armature current.

(2) The magnetic reactions of the armature currents, which cause (*a*) a reduction in voltage through the opposing action on the field (it is this demagnetising action which is chiefly responsible for the increase of drop with an inductive load), and (*b*) a local increase in the saturation of the iron which, by lowering the permeability, tends to aggravate the demagnetising action.

(3) The self-induction of the armature. This can be expressed as a reactance voltage, which reduces the terminal voltage.

(4) The eddy currents induced in the pole faces (if solid) contribute slightly to increase the drop. This effect is usually negligible.

Limits of space and the character of this work do not enable us to go into the detailed *calculation* of the pressure drop of an alternator, as the methods adopted are not at all simple. We shall therefore content ourselves with a brief explanation of the relation which the various factors concerned in the problem bear to one another. The C R drop in the armature can, of course, be immediately calculated, knowing the resistance of the winding and the current.

In Fig. 605 are shown the general relations of the effects numbered (1) and (3) above.

Let O V = the terminal E.M.F., and O A = armature current lagging behind O V by an angle ϕ. Now the armature current produces a flux in phase with itself round the conductors; this is known as a leakage flux, and in cutting the armature windings it generates a reactance voltage in quadrature with itself, and therefore in quadrature with the armature current in a manner similar to the action of leakage flux in a transformer (*q.v.*). This is represented on the diagram by V R, at right angles to O A.

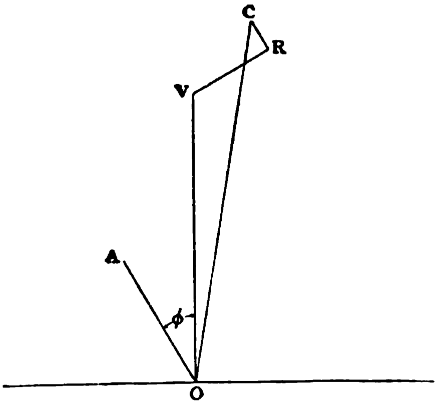


FIG. 605.—VOLTAGE DIAGRAM OF ALTERNATOR, SHOWING EFFECT OF SELF-INDUCTION.

The armature current also produces the usual C R drop, in phase with itself, and this is represented by the line R C, parallel to O A. The resultant of O V, V R, and R C, is O C, which represents the internal voltage which must be generated to produce a terminal voltage of O V.

Coming to the demagnetisation, we have to consider, first, the effect when the load is non-inductive, and, second, when inductive. We have seen that in a continuous-current armature, when the brushes are put in the neutral position, the armature currents would exercise no demagnetising effect if there were no distortion of the flux at the pole face. In practice there always is a small demagnetising effect, whatever the position of the brushes. There is an exactly similar effect in an alternator.

Consider Fig. 606, showing a single loop opposite the poles of an alternator. When the loop is in the position A B, the number of lines enclosed by the loop is changing most rapidly. Therefore, the E.M.F. generated in it is a maximum. If the load is non-inductive, there will be no difference in phase between the current and E M.F., and therefore the current will also be at its maximum, and its direction will be as shown on the diagram. This armature current will also produce a field, whose direction is shown by the small arrows. It is, therefore, obvious that the flux through the halves of the poles marked *b* and *d* will be strengthened, and that through the halves of the poles marked *a* and *c* will be weakened. In other words, the magnetic field will be *distorted*. If the flux entering the coil were unchanged, the effect would be purely distorting, but, owing to the distortion changing the relative positions of the flux and coil, there is also some demagnetising

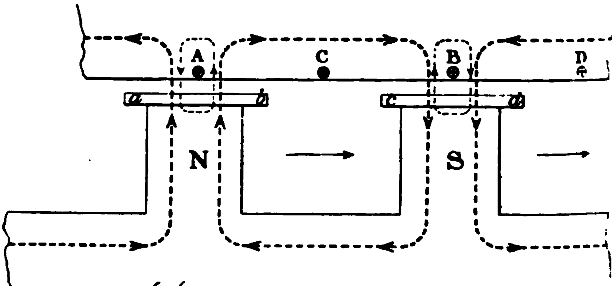


FIG. 606.—DIAGRAM EXPLANATORY OF ALTERNATOR ARMATURE REACTION.

effect. Now consider the extreme case when the current lags by a one-quarter period behind the voltage. Then, when the loop has taken up the position C D, exactly over a pole, the current will be at its maximum, and the effect of its ampere turns, directly opposing those of the field, will be purely a demagnetising one. For differences of phase intermediate between the two cases given the demagnetising effect will be proportional to the sine of the total angle of lag between the maxima of the current and flux curves.

In addition to the above, we have the demagnetising effect proper of the armature. Suppose we wish to find what excitation an alternator will take at full inductive load. We first, by the aid of a series of magnetic tables, plot a curve connecting voltage at no load and ampere turns per pole on the field, as has been explained previously in Chapters I. and III. We calculate the reactance voltage and C R drop, and compound them with the terminal voltage as shown in Fig. 605. Then, from our no-load curve, Fig. 607, we find the excitation O X required to produce this internal voltage O V_1. To this excitation we add X M, equal to the effective demagnetising ampere turns of the armature on an inductive load of the specified power factor, together with a small extra number of ampere turns due to the increased field leakage consequent upon increasing the magnetomotive force on the pole. The sum of the above ampere turns (O M) gives the excitation required at full inductive load. The voltage O E on the no-load curve corresponding to this excitation (O M), is that to which the terminal voltage would rise on switching off full non-inductive load. To get the voltage obtained when full inductive load is switched on (speed and excitation being constant), the above procedure is reversed.

From the ampere turns required to produce normal voltage at no-load are subtracted the demagnetising ampere turns, and the corresponding voltage is obtained from the no-load curve. From this voltage are vectorially subtracted R V and C R, and the resultant terminal voltage O V is obtained. The calculation of the reactance voltage and the demagnetising and distorting ampere turns, is too lengthy and complicated to be gone into in a work of the elementary character of the present one.

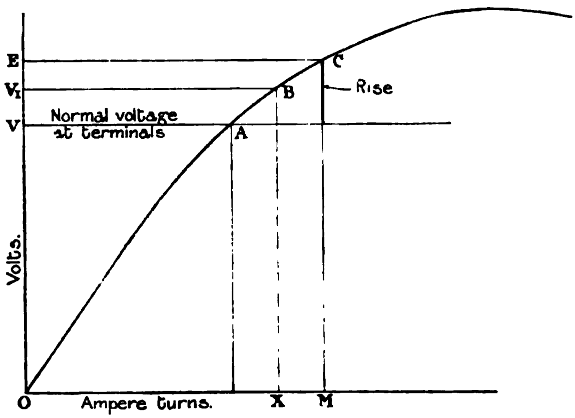


FIG. 607.—SATURATION CURVE OF ALTERNATOR.

It will now be seen why the rise in pressure when full inductive load is switched off is less than the fall in pressure when full inductive load is switched on. In the first case, the ampere turns on the field magnets which are, on load being taken off, no longer required to balance the demagnetising ampere turns on the armature, move the working point of the machine *up* the saturation curve from the point B. As the curve is rapidly turning over at this point, the effect on the voltage is comparatively small.

In the second case, the ampere turns which are required to balance the demagnetising action of the armature when load is put on, and which are, therefore, not available to magnetise the machine, cause the working point to move *down* the saturation curve. As the curve is here nearly a straight line, the effect on the voltage is comparatively large. We thus see that the difference between the rise and fall of voltage depends on the saturation of the machine.

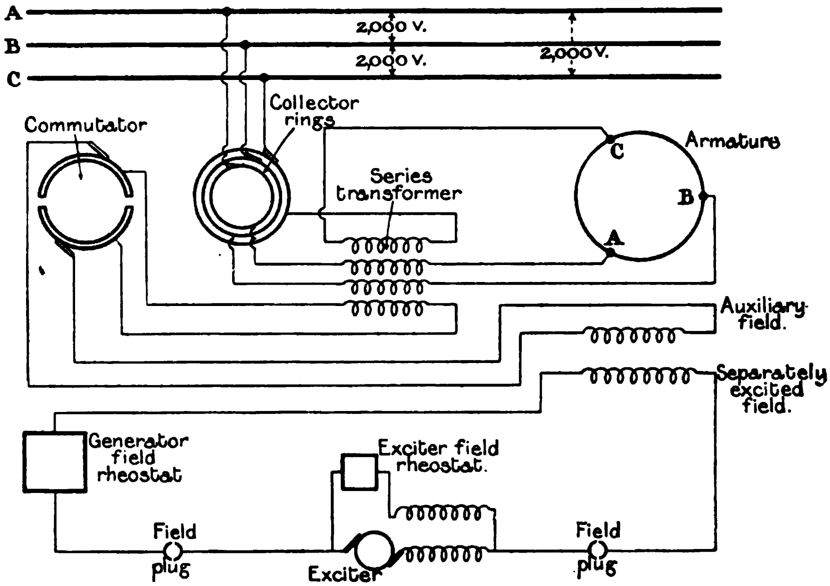


FIG. 608.—CONNECTIONS OF WESTINGHOUSE COMPOSITE-WOUND THREE-PHASE GENERATOR.

COMPOUNDING OF ALTERNATORS.

Considerable attention has been given of recent years to methods and devices by which the pressure variations of an alternator may be corrected automatically by a compensation effected by the load itself. The various methods employed may be roughly classified as follows :—

1. By sending a rectified current proportional to the load current round the field magnets of the alternator.

2. By compounding the exciter with a rectified current proportional to the load current.

3. By causing the distorting effect of the load current to *increase* the effective magnetism threading the armature.

4. By having an automatically controlled resistance in the excitation of the alternator.

The rectified current for the first method is practically always obtained by the use of a commutator of some sort, electrolytic and vacuum rectifiers not having as yet found any extensive application for this purpose, on account of their unreliability.

A simple case of compounding by rectified current is that of the Westinghouse composite-wound generator, a diagram of which is shown in Fig. 608. Current is taken from the alternator armature through a series transformer, the secondary current of which is proportional to the primary load, and this secondary current after having been rectified by means of a commutator, is passed round an auxiliary winding on the alternator field magnets, thus increasing the excitation with an increase of load.

The arrangement is good for circuits of

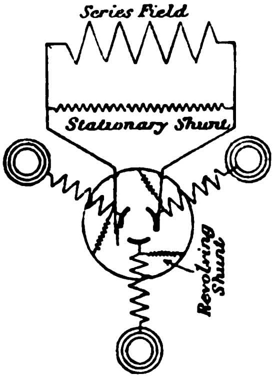


FIG. 609.—DIAGRAM ILLUSTRATING GENERAL ELECTRIC COMPANY'S METHOD OF COMPOUNDING ALTERNATORS.

high power factor, but is of little value on an inductive load, especially if the generator has a poor characteristic on such loads.

The General Electric Company of America have used the arrangement shown in Fig. 609. In this case the three ends of a star armature winding are connected to a commutator instead of the ordinary common junction. The resistances shunting the commutator to reduce sparking are shown in the diagram, as is also the shunt across the series field winding, which is used to adjust the degree of compounding provided. The series field winding thus receives a unidirectional current proportional to the load. The commutator shown is a three-part one for a two-pole machine. A ten-pole machine would have a fifteen-part communtator and so on.

Heyland has devised a very successful, machine in which three-phase current is led by brushes into a special commutator, and thereby converted into direct current and fed into a number of field windings in parallel.

The commutator bars are bridged by non-inductive resistances to suppress sparking, and so to aid commutation.

The current supplied to this commutator is obtained from two transformers, one of which is connected in series with the load and the other as a shunt. The result of combining these two currents is that when the load increases the resultant three-phase currents increase, and the lower the power-factor the greater the increase. The method is illustrated in Fig. 610, the diagram relating to a two-pole imaginary case. The parallel field windings are shown at *r*, and the commutator resistances at ρ. The currents in various branches are indicated in terms of the current, i, flowing in one field winding, and the current in the brushes, I., II. and III., at the instant shown are C_1, C_2 and C_3.

When it is desired to compound by means of the exciter, the rectified currents obtained by one of the methods described above may be passed round the field system of the exciter and thus be made to increase the main generator volts by increasing the exciting current. In most

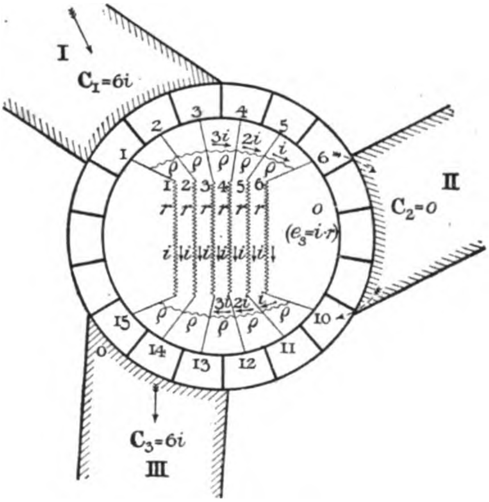


FIG. 610.—HEYLAND'S METHOD OF COMPOUNDING THREE-PHASE GENERATOR.

cases, however, the exciter is compounded by the action of an alternating current in its armature.

If an alternating current is led into a continuous-current armature by slip rings, into either special or the working windings, it re-acts upon the field in a manner which varies with the phase of the alternating current.

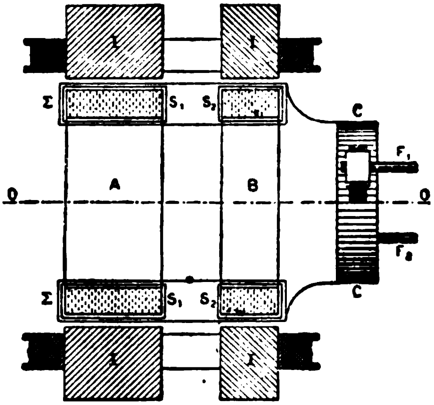


FIG. 611.—LEBLANC'S EXCITER.

This is taken advantage of in the following way. The exciter is either direct driven or otherwise made to run synchronously with the generator, and if not direct connected, is provided with slip rings. The rings or leading-in wires are connected to points on the armature, such that when the main generator current is led into the slip rings it leads upon the exciter E.M.F. at those points. This has the effect of compounding the exciter, and of increasing the voltage of the machine. Usually a current proportional to, and having a fixed phase relation to, the main generator current is used. This is obtained by means of transformers, and gets over voltage and other difficulties attendant upon the introduction of current direct from the main generator.

A type of exciter constructed by Leblanc consists of two ring windings on a common shaft, one being connected in series and the other in parallel with the main alternating current, a direct-current winding is wound over these two and connected to a commutator. The machine runs as a synchronous motor, driven by the currents in the series and shunt ring windings, and gives out at its commutator an exciting current which is increased by an increase of load or a decrease of power factor. The operation of this machine is very perfect, the main generator terminal volts being kept extraordinarily constant for any kind and any variation of load.

The machine is shown diagramatically in Fig. 611 and its connections in Fig. 612.

The third method enumerated requires a specially-designed pole on the alternating current generator, consisting of at least two parts, viz. the main pole, which is magnetised by the exciter as usual, and a smaller pole which is magnetised only by armature reaction.

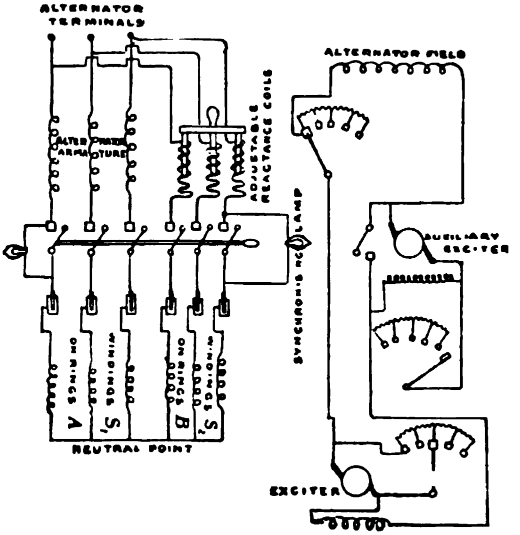


FIG. 612.—CONNECTIONS IN LEBLANC'S METHOD.

The main pole is magnetised by the main magnetising coil, and in some cases another coil may be used encircling both poles. This second coil may be necessary to vary the normal voltage of the machine.

The action may be very briefly described as follows: Any current in the armature in phase, or nearly in phase, with the E.M.F. will tend to demagnetise the saturated part of the pole and to magnetise the unsaturated part. The flux in the saturated part cannot be altered to any great extent, but the smaller pole becomes more or less highly magnetised, and so increases the E.M.F. of the machine. For power factors above 0·85 such machines can be made to hold their voltage from no load to full load. But with low power-factors the regulation will be worse than with no compounding at all.

M. Thury has designed an automatic regulator in which the contacts which put resistance in or out of the field are moved mechanically, but which is controlled electrically.

A pulley driven from the main engine operates the contacts through one or other of two bevel wheels, one of which puts resistance into the circuit and the other takes resistance out. The motion of the bevel wheels is controlled by a solenoid, connected as a shunt across the mains in such a manner that if the volts drop resistance is cut out of the circuit, while if they rise it is inserted; if the voltage remains steady both wheels are out of gear.

Tirrel has more recently invented a very successful device in which the regulation is effected by varying the terminal pressure of the shunt-wound exciter, while keeping the resistance of the generator excitation circuit constant. A short-circuiting contact, arranged in parallel with the shunt resistance of the exciting dynamo, is made to open and close some hundreds of times per minute by means of a vibrating lever; the longer this contact remains closed at each vibration, the greater will be the average value of the current thus short-circuited, and therefore the higher the terminal pressure of the exciter.

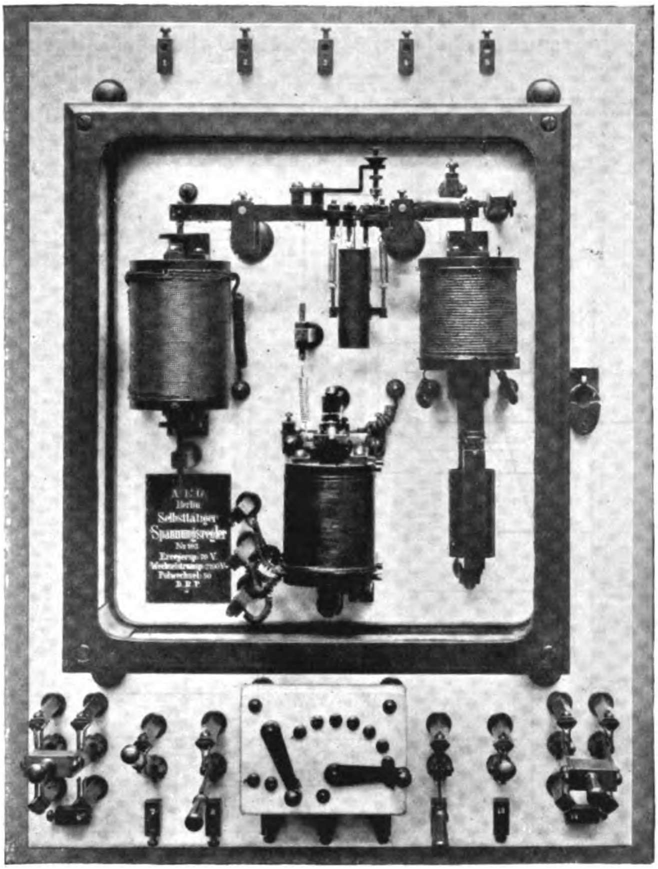


FIG. 613.—TIRREL VOLTAGE REGULATOR PANEL.

The main current regulator in the excitation circuit of the generator is either short-circuited, or nearly so; it should not however, be dispensed with, being necessary for paralleling in the case of two or more generators having the same source of excitation.

The principal parts of the apparatus can be seen in diagrammatic form in Fig. 614.

The short-circuiting contact, *rs* (relay contact), parallel to the exciter shunt regulator, is closed by the action of the spring at the end of the lever, *p*, and opened by the pull of the relay magnet, *a*, a condenser being arranged across the short-circuiting points to prevent sparking. The relay magnet has two windings which exactly neutralise each other, both receiving current from the same source. The winding, *m*, being permanently connected to the terminals of the exciter, the action of the relay will be neutralised as soon as the winding, *n*, is also connected to the same terminals by closing the main contact, *d e*, this latter being a vibrating contact, opening and closing some hundreds of times in a minute.

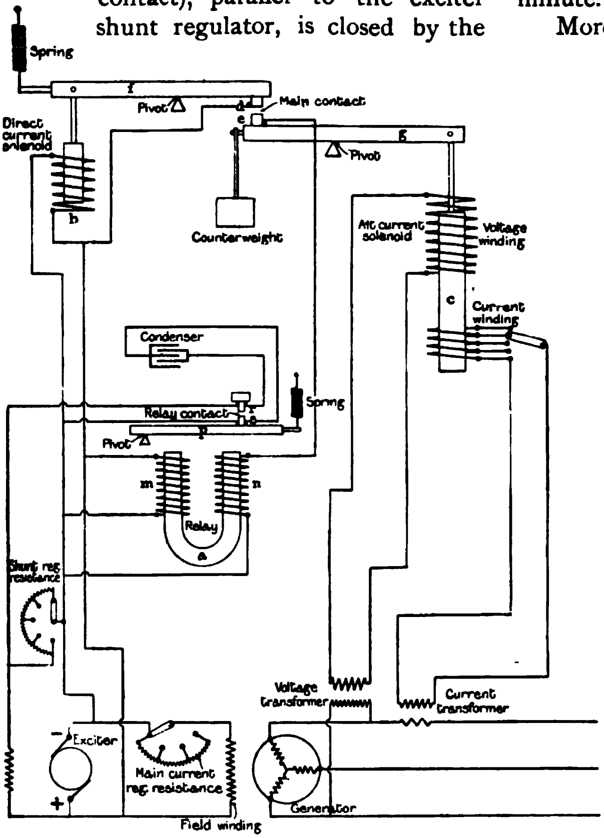


FIG. 614.—CIRCUITS OF TIRREL VOLTAGE REGULATOR.

Moreover the distance between the contact points of this main contact is variable, being governed on the one hand by the direct current solenoid, *b*, depending upon the terminal pressure of the exciter, and on the other hand by the alternate current solenoid, *c*, depending upon the terminal pressure of the generator, and, in the case where overcompounding is desired also upon the load on the generator.

It is obvious that the opening and closing of the relay contact, *r s*, is governed by the opening and closing of the main contact, *d e*, the object of this arrangement being to allow of the actual short-circuiting contact being well dimensioned to prevent undue wear without in any way affecting its sensitiveness, the main contact, *de*, being made very light and sensitive. The action however, as far as outside effect is concerned, would be the same if the relay contact were left out, and for simplicity's sake we will imagine this to be the case, the main contact, *de*, being also the actual short-circuiting contact.

We will take the typical case of a standard generator with a built-on exciter giving a terminal pressure of 100 volts, the generator requiring, say, 70 volts for excitation under normal working conditions. We will first imagine the solenoid, *c*, out of action and the lever, *g*, held in a middle position, the direct current solenoid bringing the upper contact into such a position that the average value of the current thus shunted corresponds to a terminal pressure of the exciter of 70 volts.

If now the solenoid, *c*, be brought into circuit and adjusted till the required generator pressure be maintained, it will be found that as soon as the generator pressure falls, the action of this solenoid will bring the contact points nearer together, causing a larger average excitation shunt current to flow, thereby raising the pressure of the generator.

Where over-compounding is desired, a second current winding is arranged on this solenoid, fed from the main bus-bars through a regulating current transformer.

The above description is based upon the case of a single generator, but by employing two or more such regulators, any combination of generators and exciters can be regulated.

A complete regulator is shown in Fig. 613, where all the parts are easily seen.

The advantage of these regulators over mechanical regulating devices consists in the small number and extreme lightness of the moving parts employed, and, unlike purely electrical regulators, they can be fitted to any standard generator and exciting set without any alteration being necessary to either.

SECTION VIII.

LIGHTING AND METERS.

CHAPTER I.—LAMPS.

INCANDESCENT CARBON FILAMENT LAMPS—METALLIC FILAMENT LAMPS—ARC LAMPS—ARC LAMP MECHANISMS—EXAMPLES OF ARC LAMPS—PHOTOMETRY—STANDARDS OF LIGHT—PHOTOMETERS—THE PURKINJE PHENOMENON.

One of the most important factors affecting the supply of energy for lighting purposes is the apparatus available for utilising the energy. It is not merely that there must be lamps, but that the general characteristics and behaviour of the lamps exercise a powerful control on the whole undertaking. The lack of an incandescent lamp having favourable properties was responsible for delaying electric lighting for many years. Of all the processes suggested for the making of the filament, and of the numerous ones tried commercially, but two remain in use to-day, and of the two one seems to be dying rapidly. Both these processes consist in the preparation of cellulose threads, which have subsequently to be carbonised. The more general process consists in dissolving cotton wool in a solution of zinc chloride and then forcing the solution through fine jets into a drying solution of acidified alcohol. The stream issuing from the jet at once solidifies into a flexible gelatinous thread, which has become practically pure amyloid. The chief difficulty is that of producing a uniform thread. Two obstacles to this end arise. The solution in zinc chloride turns very viscous, and since the cotton wool entraps much air, the large air bubbles escape very slowly, and very small ones not at all, but have to be removed. Unless removed they would be found enclosed in the thread, fine as it is, and would cause fatal non-uniformity. The other difficulty arises from the need of keeping the rate of flow of the fluid through the jet constant. There is a tendency for the syrupy solution to become somewhat lumpy, so varying the flow through the jets. These difficulties are met by constant stirring during the dissolving process, and by drawing the solution under vacuum through filtering material to remove bubbles and any solid particles. The fluid, having been thus made uniform in consistency and free from bubbles, is forced by air pressure, carefully kept constant, through the jets. After several days' treatment with alcohol, followed by twenty to thirty hours washing in water, the thread is wound on drums, each carrying about half a mile of filament and about three feet in diameter, to dry. When dry, the thread is wound on formers in hanks. The formers are made of carbon and, when filled, are placed in closed plumbago crucibles and fired at a very high temperature. This effectually dehydrates the material and reduces the thread to pure carbon. It is then very hard, lustrous and brittle, and is permanently set to the shape of the former. Connection is made to the filament (*i.e.* the carbon thread) by platinum leading-in wires, and these are jointed to short copper leads which are united to the ends of the filament by deposited carbon. One end of each copper wire is flattened and shaped to a hollow cone, into which one end of the filament is inserted, the cone being then pinched so as to nip the filament. Carbon is deposited on this joint either by heating the joint under benzine, or by applying a cement which is afterwards carbonised by being fired.

The other method referred to of preparing the filament consists in treating cotton thread instead of cotton wool. Cotton thread is treated with sulphuric acid for a few seconds, washed and dried. The thread is exceedingly tender after the acid has acted upon it, and must be very thoroughly washed to eliminate every trace of acid. On drying, the thread contracts considerably and hardens also. It is also of irregular size and must be drawn through dies to cut it to a uniform diameter. The mounting and subsequent treatment are the same for both processes.

Although the filament may, when prepared by either process, have a practically uniform diameter, it will not necessarily have uniform electrical qualities throughout, and if the resistance be higher in one place than in another, that portion will glow more brightly than the rest, and have a shorter life than the rest. To prevent this, the filament is placed in a hydrocarbon vapour derived usually from benzine, and current is then passed through it until it incandesces. At this temperature the vapour is decomposed and carbon is deposited on the filament at a rate depending upon the temperature of the filament. Thus the hotter places receive the heavier coating. The process is continued until the resistance of the filament has been reduced to a predetermined value.

The glass bulbs to contain the filaments are provided with a narrow glass tube attached to the blunt end, and with a small open neck at the other end. A high voltage lamp has its filament mounted on the end of a glass tube, and the tube is inserted into the opening of the bulb, the opening is then closed under the blowpipe, so fusing the edges of the opening to the tubular mount. The filament for a low voltage lamp is simply inserted into the bulb, the open end of the bulb is softened under the blowpipe and the walls carefully pinched on to the platinum wires. It is of extreme importance that this seal should be absolutely perfect in order that air may not subsequently enter by it. Various substitutes have been suggested for platinum, but so far none has proved commercially as good.

The lamp is then connected by means of the narrow tube just referred to, to a vacuum pump, and exhausted to a very high degree. As a rule a preliminary exhaustion is carried out by means of a mechanical pump, and the process is finished by means of a mercury pump. When exhaustion is complete the final seal is made by a fine blowpipe jet applied to the junction of the exhaust tube and the bulb, and the former is drawn off, leaving the familiar pip on the end of the bulb. The platinum wires are next connected to small brass plates, or other suitable contact devices, to fit the various lamp holders in use, the contacts being kept in position by plaster of Paris, or preferably, some harder setting cement, or in the case of high voltage lamps, by a vitreous cement, such as vitrite, employed by the Robertson Lamp Company.

One of the chief difficulties in obtaining a high vacuum is the tendency of the filament, which is somewhat porous, to occlude oxygen. A chemical process of exhaustion is sometimes employed following the mechanical pump, in which an easily oxidisable unstable substance previously placed in the exhaust tube is strongly heated. This breaks up and the filament is at the same time incandesced, with the result that the oxygen combines with the substance referred to to form a solid. When the combination is complete the exhaust tube is removed as before. The fact that 25 grammes of charcoal at the temperature of liquid air will absorb about 8 litres of air is also made use of by some firms.

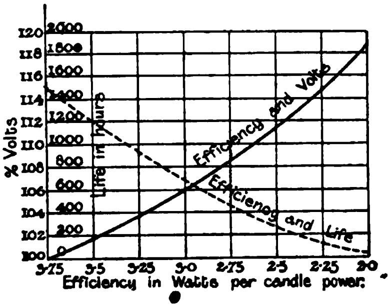


FIG. 615.—TYPICAL CURVES FOR LAMP FILAMENTS (ACTUAL LIFE).

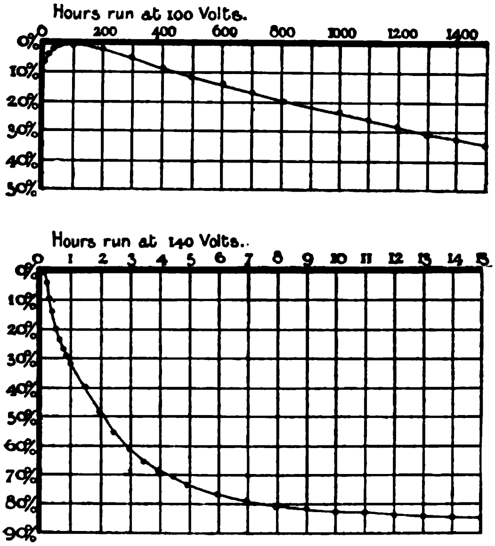


FIG. 616.—RELATION BETWEEN CANDLE POWER AND AGE OF CARBON LAMP RATED AT 4·5 WATTS PER CANDLE POWER, RUN AT NORMAL VOLTAGE, AND 40 PER CENT. EXCESS VOLTAGE RESPECTIVELY.

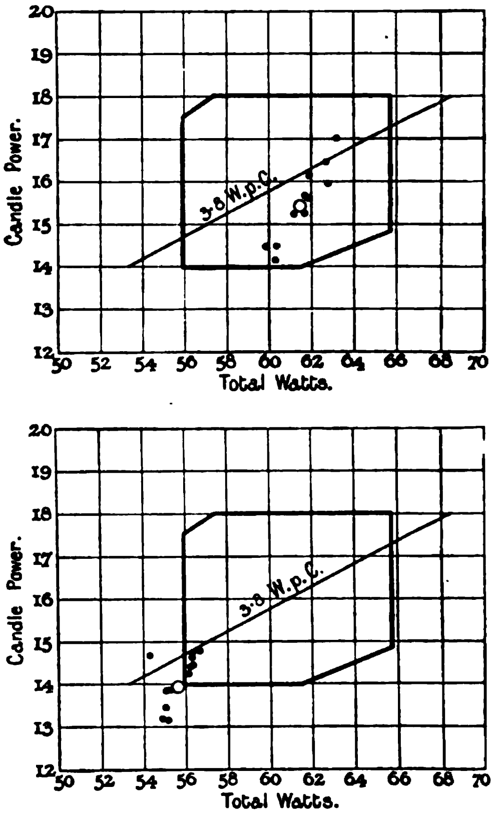


FIG. 617.—DIAGRAMS ILLUSTRATING ACCURACY OF RATING OF CARBON LAMPS. LOWER DIAGRAM SHOWS MORE UNIFORM MANUFACTURE AND UPPER MORE ACCURATE RATING.

Lamps are commonly classed according to the candle power and voltage at which they are intended to work, and these again depend upon the efficiency and life to be attained. The life of a lamp bears some inverse proportion to its efficiency, as shown in Fig. 615, so that, roughly speaking, one which should have a life of 1,000 hours will usually have an efficiency (or rather an inefficiency) of 4 watts per candle power; while one with a life of 400 to 500 hours will consume only about 3 watts per candle power.

The intention of the consumer respecting life and efficiency will be regulated by the relation between the price of the lamp and the price of the electric supply. If the supply is expensive and lamps reasonably cheap it will pay him to use a lamp of 3 watts per candle power, and throw it away after 400 hours' burning; but if current is cheap and lamps are dear, he will choose long-life inefficient lamps. Fig. 616 contains curves which show the falling off of candle power with time at normal and 40 per cent. excess voltage respectively. Fig. 617 consists of useful diagrams by which to check the accuracy of manufacture and rating of carbon lamps. Space forbids a more detailed enquiry into this important point, and the reader is referred to the extensive literature on the subject, and to the *Proceedings* of the Institution of Electrical Engineers, Vol. XXXVIII., from which the above four figures are taken.

METALLIC FILAMENT LAMPS.

There has been of recent years a very determined, and indeed, successful attempt to return to lamps having metallic filaments. The carbon filament has a disadvantage in that the temperature coefficient of its resistance is negative, so that an increase of voltage above the normal occasions a more than proportionate increase of current. This greatly reduces the life of the lamp, and causes considerable fluctuation in its brilliance, even though the fluctuation in voltage be not very great (*see* Figs. 615 and 618).

A metallic filament, on the other hand, has the usual positive temperature coefficient (*see* page 14), and is therefore better balanced, *i.e.* variations in voltage are partly compensated for. The difficulty has been to obtain a metal having a sufficiently high fusing point, for the light-giving power of a given surface is almost wholly a question of temperature. Platinum was used by some of the very earliest experimenters prior to the advent of the carbon lamp, but its fusing temperature is far too low. The modern filaments consist of such rare metals as osmium, tungsten, and tantalum, but owing to the lowness of their specific resistance and poor ductility very great difficulty has been experienced in producing sufficiently thin filaments. A little consideration will show that since the power consumed by the lamp is inversely proportional to the resistance, some 330 ohms are necessary to give a 30 watt lamp on a 100 volt circuit, or a 120 watt lamp on a 200 volt circuit. If this resistance can only be obtained in a very long filament, the illuminating surface will be great, and the lamp as a unit of light inconveniently large, even if it be not also cumbrous,

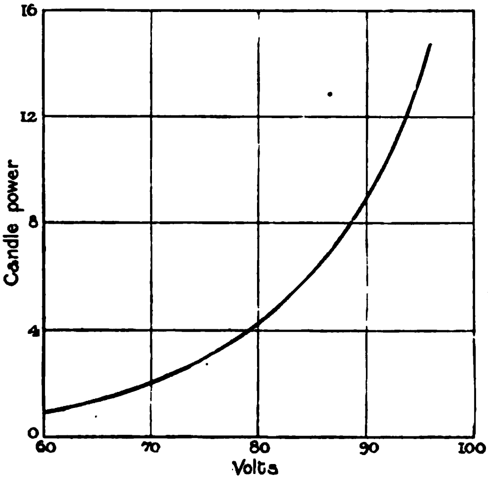


FIG. 618.—CANDLE-POWER VOLTAGE CURVE OF 95 VOLT CARBON LAMP.

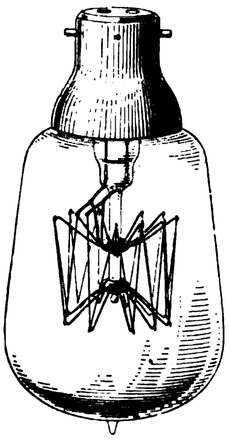


FIG. 619.—MODERN TANTALUM LAMP FOR 100 VOLTS.

owing to the large bulb required to contain the lengthy filament. The conductivity of the metals, therefore, has necessitated the use of wires very much finer than the thinnest carbon filaments. The fineness of the wires (2 mils or $\frac{1}{500}$ of an inch) makes the lamps very tender, even though the filament (wire) is supported at numerous points. This detail is seen in the tantalum lamp illustrated in Fig. 619. This lamp is, however, fairly strong until it has been running some two or three hundred hours, after which it is as brittle as others. Most metallic filament lamps may be mended when the filament breaks in one place by shaking the ends together while current is "on." The moment the ends touch they weld together. Remarkable ingenuity has been exhibited in the manufacture of these lamps. The tantalum filament is made by preparing a paste of a salt of tantalum and some binding material, such as gum tragacanth, which is squirted into a thread; it is then heated and the binding material driven off while the salt is reduced to metallic tantalum, which welds into a continuous wire. The tungsten lamp is prepared by depositing an oxide of tungsten on a carbon filament and then burning away the carbon and reducing the oxide at the same time, so leaving a tungsten *tube* of the desired shape; the thickness of the deposit is controllable through a fairly wide range.

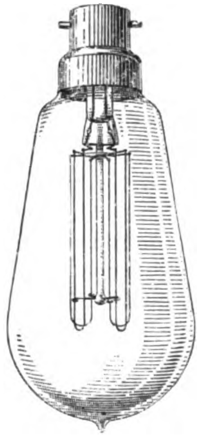


FIG. 620.—100-VOLT OSRAM LAMP.

The osmium lamp is now replaced by one made from an alloy of osmium and tungsten, known as the "osram" lamp, shown in Fig. 620.*

The metals used are all hard and brittle, and cannot be drawn into wires by usual methods. The light from these lamps is exceptionally white, owing to the very high temperature at which they are worked, made possible by the high melting points of the metals. To this is due their high efficiency, ranging from about 1 watt per candle in the tungsten to about 1·4 in the tantalum.

A very different lamp, and one forming a class by itself, is the Nernst lamp. Nernst uses as filament a glower made of a rod of oxides of rare earths such as zirconia and yttria. Ordinarily such materials are non-conductors, but will conduct if hot. He therefore adds a heating resistance which is automatically cut out by a relay when the glower begins to conduct sufficiently. At that point the heat developed in the glower itself by the current is enough to keep it at a white heat. The glower is so sensitive (as regards its resistance) to changes in temperature, which would follow changes of voltage, that a steadying resistance is provided in series with it. This is of iron wire so adjusted that its rise in resistance closely compensates for the fall in the glower resistance. The iron wire is exceedingly fine, and is contained in an exhausted glass bulb to protect it mechanically and from oxidation. In a 230 volt lamp the iron absorbs about 20 volts, and in a 100 volt lamp about

---

* The last syllable, "ram," is the last of the Continental name for tungsten, "wolfram."

10 volts. The efficiency of the lamp is about 1·5 watts per candle power.

The Nernst lamp, in common with the tantalum, does not work well on alternating-supply circuits, the life being very much shorter (about half) than on continuous-current supply.

ARC LAMPS.

The principle of the arc lamp is as follows: If the ends of two carbon rods are brought together and a current is made to pass across the junction, nothing particular happens, but if the points are then separated heat is at once developed at such a rate that the carbon points burst out into brilliant incandescence and a vivid light is the result. The probability is that just at the instant when contact between the carbons is about to cease, the last minute fragment which bridges the gap has to carry the entire current, and thus becomes exceedingly hot. Rupture of the contact then ensues, and a spark flies across the gap, and in so doing generates sufficient heat to volatilise a small quantity of carbon. This carbon vapour at once diffuses itself in the gap and serves to conduct the current across the gap, so restoring continuity of a kind to the circuit. The carbon vapour, however, both by virtue of its resistance and the E.M.F. due to its contact with the solid carbon becomes, when carrying a current, the seat of the expenditure of a great deal of energy, which is converted into heat, so raising the carbon points to an exceedingly high temperature and maintaining the carbon vapour also in an incandescent state. The temperature, indeed, to which the carbon points are raised is probably the highest attainable on the surface of the earth, and approximates to 4,000 degrees Centigrade.

At this temperature, and when exposed to air, the carbon of course burns into CO_2, some perhaps into CO, and a very small amount of carbon vapour possibly escapes (being thus literally boiled off) and condenses in the air. The carbon volatilised at the tip of the positive rod is nearly all condensed on the negative, and the former becomes hollowed like a volcano crater, and the negative acquires a head something like a mushroom. The crater is by far the hotter of the two, and is the source of practically all the light. The column of vapour in the gap is of pale blue colour not giving much visible light but emitting a great deal of energy in actinic rays above the visible spectrum. Under these conditions, *i.e.* open to the air and supplied with a continuous current sufficient to maintain the crater at a brilliant white heat, the positive carbon burns away at about 1 inch per hour. The negative is made smaller in the ratio of about 2 to 3, and is consumed at substantially half the rate. The positive carbon is cored, *i.e.* it is formed with an axial hole through its whole length, and this hole is filled with a softer grade of carbon than the body. The core is about one-tenth the diameter of the carbon and serves to keep the crater central. The voltage across the arc is 45 when properly adjusted. It is only partly due to resistance, by far the greater part (about 40 volts) being due to a back E.M.F. between the gaseous and solid carbon. The operation of making the carbons touch and then parting them to start the arc is called "striking" it, and the subsequent movement together needed to keep the gap of constant length in spite of the burning of the carbons is called "feeding."

ENCLOSED ACTION.

In order to give a longer life to the carbons and so not only economise carbon but, what is more important, economise labour in retrimming, lamps are made to burn inside an enclosed glass globe, nearly airtight. Under these conditions the oxygen present is soon consumed after starting, and the arc burns in an atmosphere of CO and

CO_2. It behaves somewhat differently from the open arc in that a much higher voltage is required, about 70 volts across the arc, and less light is given, while the light is further of a ghastly blue colour. The lamp can be adjusted, however, to run with smaller currents than an open arc, and also to run with a much longer arc requiring a still higher voltage. The open arc is usually about $\frac{3}{8}$ inch long, while an enclosed arc may be lengthened to as much as $1\frac{1}{2}$ inch or more.

ARC LAMP MECHANISMS.

From what has been stated above it follows that the functions of any mechanism in an arc lamp are at least twofold ; firstly, the mechanism must strike the arc, and, secondly, it must feed it. These are the two prime functions of the mechanism, but there are others which come less frequently into play. If, for example, the carbon contains impurities or is of varying hardness, the mechanism should be capable of parting them still farther or of bringing them more closely together. Lamps are intended to run in one of two ways : in series or in parallel with one another. Where the number is great this is tantamount to being supplied at constant current and constant voltage respectively. For street lighting any number up to about sixty lamps (open type) may be connected in series ; for the lighting of the interiors of buildings, shop windows, etc., they are placed in parallel across ordinary constant pressure lighting mains. Series lamps were formerly fed from special arc light generators, such as those made by the Brush Company, by the Thomson-Houston Company, and by the Westinghouse Company. All these machines are series machines possessed of a drooping characteristic and other peculiarities, whereby they deliver a practically constant current throughout a wide variation in voltage. If such a machine is switched when standing still on to a long line of arc lamps, all the carbons of which are touching, and is then run up to speed, the machine is at first very nearly short-circuited, but as it is generating no voltage nothing untoward occurs ; as the current attains a value of eight or ten amperes, the carbons begin to part owing to the action of the mechanism, the voltage of the machine rises, and the mechanism further parts the carbons, finally bringing matters to a steady condition. The effect of this operation on such a generator and circuit is illustrated in Fig. 621, which is the characteristic curve of a Brush arc lighter. It will be seen that as the resistance increases, the point where the resistance line cuts the characteristic curve represents decreasing current values accompanied by increasing voltages, until the point R is reached. This is the working point of the characteristic, and the arcs are all supposed then to be burning properly. However, should a feeding mechanism for any reason fail to operate properly and the resistance further increase, it may rise to the dotted line position so that the machine gives an increased voltage to cope with this rise in resistance accompanied, however, by a very small diminution in current, with the result that the remaining lamps continue to burn about as well as before. Should the refractory lamp still refuse to feed, arrangements are made to automatically cut it out of the circuit. More recent practice, how-

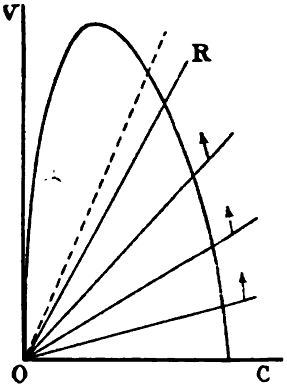


FIG. 621.—TYPICAL CHARACTERISTIC OF ARC-LIGHT DYNAMO.

ever, is to supply arc lamps from circuits fed at busbar voltage instead of from such special machines as were formerly invariably used. The light from an arc lamp is exceedingly intense. It is the electric light invariably used for all large open spaces, such as streets, promenades, etc., since it not only can be made to give a far larger amount of light than any incandescent lamp could conveniently be made to, but it produces the light with a much smaller expenditure of energy than does an incandescent one.

SOLENOID ARC LAMPS.

A lamp by Messrs. Crompton is illustrated diagrammatically in Figs. 622 and 623. The mechanism of this lamp is best understood by describing the action of the lamp from the moment of being switched on to a circuit. The carbons are in contact when the circuit is established and the series coil *a* (Fig. 623) is strongly energised ; pulling down its core *b* it oscillates the lever *c*, a dash-pot *d* preventing the movement from being too violent. The opposite arm of the lever *c* being raised tightens the brake cord or chain *e* upon the brake drum *f*, and imparts a small amount of rotary movement to the drum, thus turning the drum *g*, around which positive and negative cords are wound. This separates the carbon tips, and the arc is struck, the pull of the shunt coil *h* upon its core *j* simultaneously increasing and counteracting the pull of the series coil *a*. The other end of the brake cord *e* is fastened to a blade spring, so that when the cord *e* is pulled, the spring is deflected upwards and tends to assist the shunt coil *h*. As the arc burns to a greater length the shunt coil increases in strength, and, with the assistance of the spring, gradually overcomes the pull of the series coil, thus rotating the drum in the opposite direction to feed the carbons together. When the blade spring is straight it no longer

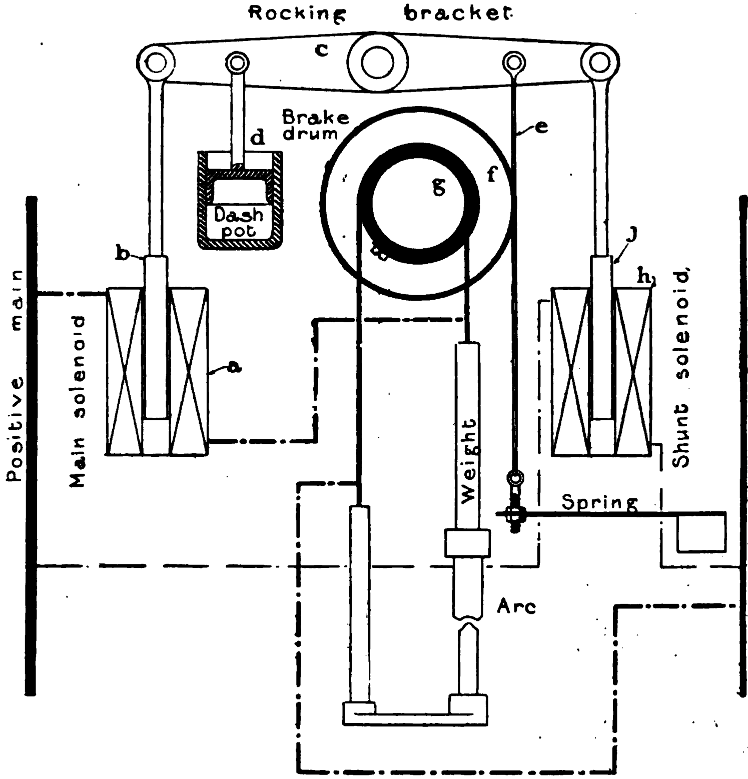


FIG. 622.—SEE-SAW SOLENOID CIRCUITS OF CROMPTON ARC LAMP.

assists the coil *h*, and if the latter coil continues to overcome the pull of the coil *a*, owing to the length of arc being too great, the brake cord *e* becomes slackened, and permits the carbons to feed together by the weight of the upper carbon holder. The parts referred to in the diagram (Fig. 622) will be easily recognised in the view of the lamp in Fig. 623.

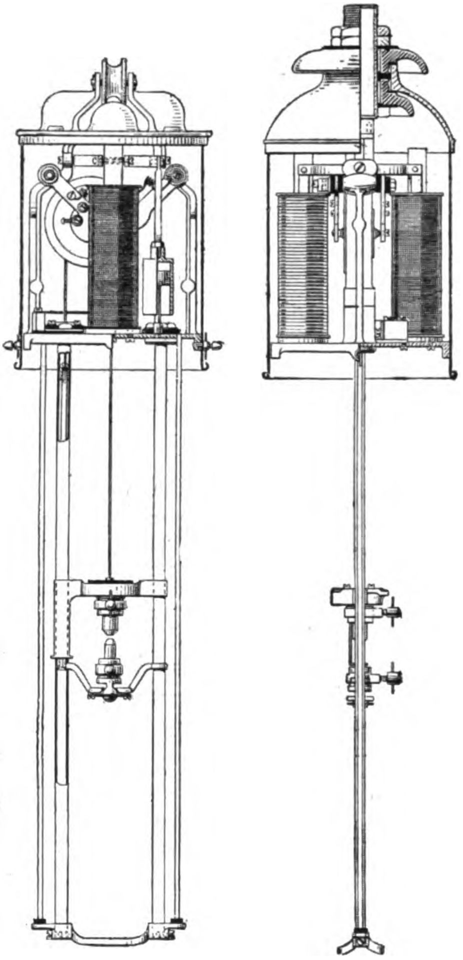


FIG. 623.—MECHANISM OF ARC LAMP HAVING SEE-SAW SOLENOIDAL CONTROL.

The "Davy" arc lamp, is noteworthy because of its extreme simplicity and fewness of parts. From the sectional view of the lamp in Fig. 624, it is seen that the top carbon *a* is inserted into a sheath or holder *b* which slides up and down in a tube *c* connecting the base plate *d* with the top plate *e*. A clutch *f* is operated by a long rod *g* pivotally connected with the lever *h*, and the lever is connected on the left with a dash-pot piston rod *j*, and on the right with the core *k* of the series solenoid *l* by a connecting rod *m*. A little to the right of the connecting rod *m* is the connection of a long, weak spring *p*, the connection consisting of a nut *o* swivelling in the lever *h*, and receiving a screw *n* connected to the free end of the spring. The nature of the spring is such that it does not produce a very greatly increasing effort when the core *k* still further pulls upon it after the striking of the arc. The tension of the spring, having been adjusted to the desired degree by the nut *o* and screw *n*, and the carbons being in contact, the series coil *l*, upon completion of the circuit, is at once energised, and pulls down the lever *h*, thus lifting the clutch *f* and the top carbon *a* and striking the arc. After the arc has been formed, a constant balancing action goes on between the coil *l* and the spring *p*, which needs no further explanation.

In order to provide a lamp which can be used direct on circuits of 200 volts and upwards the British Thomson-Houston Company arrange for two enclosed arcs to be burnt in series in one lamp. The difficulty to be overcome in such a twin-arc lamp is that of keeping the two arcs of the same length, so that the voltage shall be almost equally divided between them. In the lamp under consideration both arcs are controlled from one winding, as seen in Fig. 625, in which 6, 6^a, indicate the winding which sucks up the horse-shoe core controlling both the clutches 3 and 4. The horseshoe core carries a contact 8 which, when the core sinks far enough, engages the contact 8^a, thereby short circuiting the coils 6, 6^a, through the resistance 6^b. This causes the core to drop, thereby tripping the clutches and allowing the carbons 1, 2 to fall into contact with the carbons 1^a, 2^a. Immediately such contact takes place, the current in the windings 6, 6^a, increases sufficiently to re-strike the two arcs. Thus, by periodical and simultaneous re-striking, the two arcs are kept symmetrical.

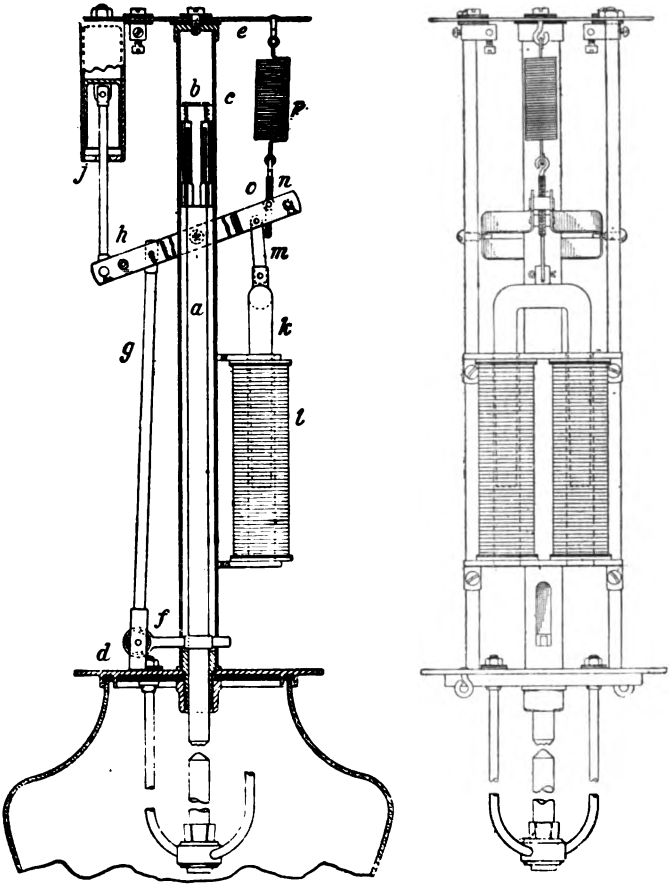


FIG. 624.—SINGLE-SOLENOID ARC LAMP MECHANISM.

HOT-WIRE LAMPS.

The Foster arc lamp successfully avoids the employment of a coil and its accompanying dash pot, and depends for its feeding action upon a hot wire working against the pull of a spring; a very interesting feature of the mechanism is the arrangement of linkages and connections whereby the spring is permitted to exert an increasing effort until the proper length of arc is reached, after which the spring exerts a decreasing effort. Thus the first rush of current has not so great an effect as the normal flow, which takes place after the arc has been established; also, any increase upon the normal flow produces a less proportional effect than does the normal flow, so that the lamp is not subject to spasmodic action even on a varying circuit. In Fig. 626 the current enters by the terminal T^1, on the right (shown in dotted lines), and by the positive lead L^1 is taken to the bottom post P^2. The hot wire or strip S is in two lengths, one length being fixed to the bottom post P^2 and carried up to a stirrup D on a rocker R, whilst the other length is connected between the stirrup D on the opposite end of the rocker, and the stirrup D on a kind of clamp H. The latter is clamped to an inclined rod or strut B (shown for clearness in three broken pieces in the figure), which is pointed at its upper end to enable it to bear pivotally within a recess in the top casting A. The point is kept up to its bearing partly by the effort of the strips and

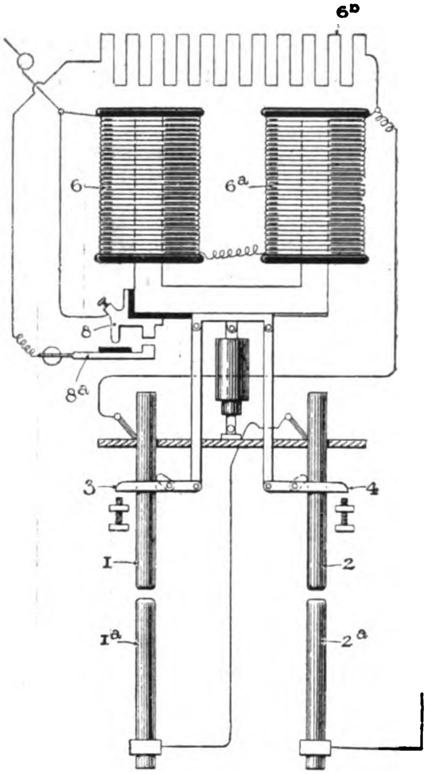


FIG. 625.—TWIN, TWO-IN-SERIES, ENCLOSED ARC LAMP.

partly by the pull transmitted by the spring Z, through the wheel M and the link N, which latter is connected to the clamp H. The upper carbon clutch Cl is of the usual kind, and is pivotally connected to an arm which is mounted on the axis of the wheel M in such a manner that there is a certain amount of lost motion of the wheel before the arm is moved to operate the clutch. The end of the upper carbon is inserted into a sheath C_S and moves in the tube G. A regulating screw S_C is provided for adjusting the position of the top post P^1 in order to put more or less tension on the strip S. The circuit is as follows. From the terminal T^1 through the positive lead L^1 to the bottom post P^2, through the strip S, and thence through the flexible lead Fl to the top carbon, thence through the lower carbon and the framing B_R to the negative lead L^2.

When the lamp circuit is closed the rush of current heats up the strip S, which expands, thereby permitting the strut rod B to move pendulum-wise under the pull of the spring Z through the agency of the wheel M and link N. At first the movement of the wheel M has no effect upon the clutch, but the continued expansion of the strip S, and further turning of the wheel, at last causes an arm (not seen in the figure) to raise the clutch Cl, and with it the carbon. Owing to the point chosen for the connection of the spring Z with the wheel, the leverage with which the

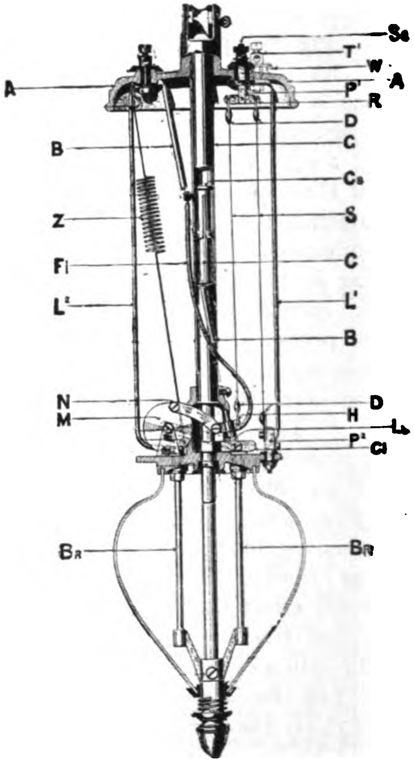


FIG. 626.—HOT-WIRE ARC LAMP.

spring has been exerting its pull up to this point has been an increasing one; but now that the normal arc length has been reached, any increase in current and consequent further expansion of the strip S and movement of the wheel M will cause the spring to work with a decreasing leverage, so that a sudden increase in the strength of the current does not cause such a jump in the arc as otherwise would be the case. When the arc gets too long the strips, owing to the decreased current flow, begins to cool and, contracting, begins to overcome the pull of the spring *z*, so that the clutch *cl* is lowered, and permits the carbon to feed under gravity. These lamps have been switched over while burning from a continuous-current circuit to an alternating-current circuit without the arc breaking, thus showing their extreme adaptability for all conditions.

FLAME ARC LAMPS.

The flame arc is usually produced between carbon electrodes which have had incorporated with them certain salts which become volatilised, and are consumed in the arc, imparting to it a particular colour and great brilliancy. When electrodes of this description are used, great difficulty arises from the scorial and slag produced. The carbons are therefore commonly arranged in the lamp at an angle to one another, so that they represent the letter V. The arc is known as an intensive flame arc, because, being formed at the apex of the angle between the lower ends of the electrodes, an intensified heating and combustion results. The impregnated or compound electrode burns much faster than the ordinary carbon electrode, and in view of the fact that greater constancy in the position of the arc upon the electrodes results from using an electrode of small diameter, the makers of intensive flame arc lamps have to provide for electrodes of comparatively great length if the lamps are required to burn for a number of hours without retrimming.

The "Excello" arc lamp is a lamp of the intensive flame type, and the principle of working is seen from the diagrammatic illustration, Fig. 627. The lower end of the right-hand electrode is engaged by a slider *d*. A long bent rod *b* is connected at its lower end by a small linkage with the slider *d*, and at its upper end is connected with the pivoted armature *e*. The armature *e* forms part of a centrally pivoted member having a dash-pot arm (seen to the left) and a detent arm (seen to the right), the detent being in engagement with the fly or air vane of a clockwork train. When the lamp is not in use the carbons are apart, but as soon as the lamp switch is closed the shunt coil *n* attracts the armature *e*, which lifts the rod *b*, and thus moves the slider *d* to bring one carbon

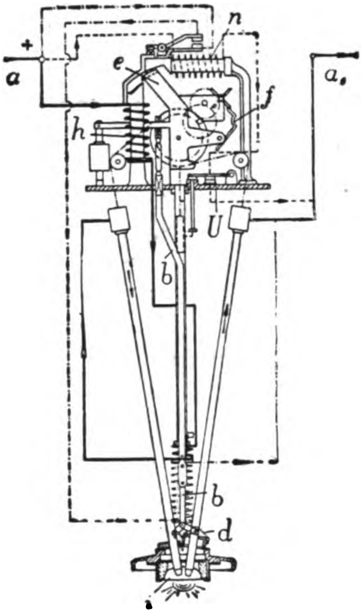


FIG. 627.—EXCELLO FLAME LAMP; INTENSIVE TYPE.

into contact with the other, the carbons are at the same time free to descend, owing to the detent being moved free of the clockwork train. At the moment of contact a strong current passes through the carbons and the series winding *h*, and the latter pulls over the armature *e*, thereby stopping the clockwork train and depressing the rod *b*, which pushes the right-hand carbon away from the left-hand one and the arc is struck. When the arc lengthens the pull of the coil *n* predominates, and the rod *b* is lifted, thereby decreasing the distance between the tips of the carbons and releasing the clockwork, which then permits the carbons to descend. The functions of the cap *i* are: to protect the arc from draught; to keep the gases of combustion around the arc and prevent, to some extent, the access of oxygen thereto; to increase the temperature of the arc; and to serve as a reflector. When the carbons are nearly burnt out, a small detent, moved up the middle rod by a chain as the carbons are fed downwards, opens a carbon-faced switch U by striking a rod, and the shunt coil *n* is thus de-energised. This permits the series coil *h* to pull the armature *e* right over, and break the arc. In the figure a series coil is seen around the rod *b*, the effect of which is magnetically to deflect the arc downwards. When the lamp is on a high-voltage circuit a second coil (seen in dotted lines) is provided beneath the one just described, and is connected across the arc. When the circuit of the coil *n* is broken, as stated, the circuit of the coil in dotted lines is completed by the closing of the switch seen just above the coil *n*, the coil (shown dotted), strongly magnetised, acts as a magnetic blow out, which ensures the extinction of the arc.

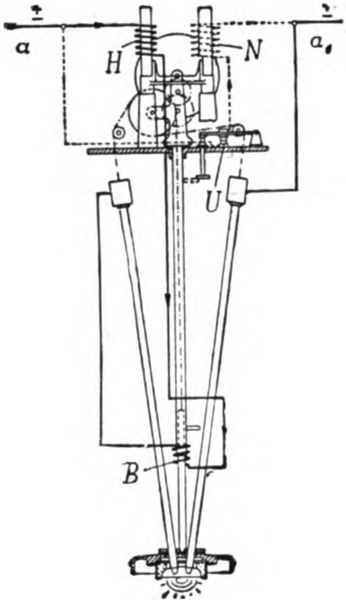
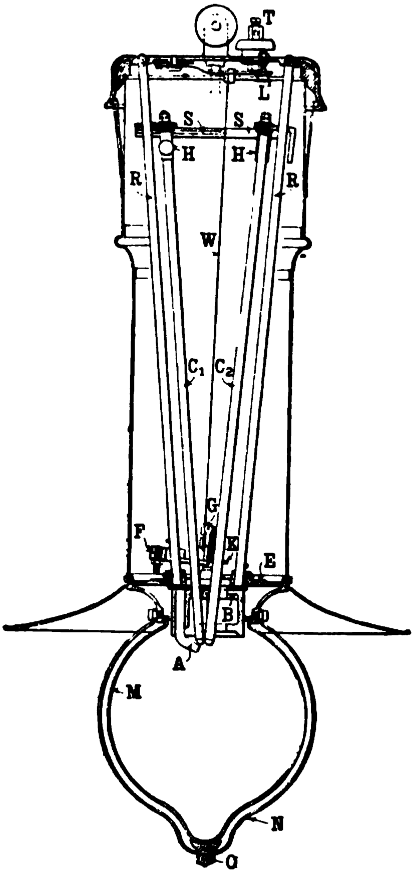


FIG. 628.—EXCELLO FLAME LAMP FOR ALTERNATING CURRENT.

The Excello lamp for alternating current is seen in Fig. 628, and some of its details are the same as those in the direct-current lamp just described. A motor disc driven in one direction by a series coil H, and in the other direction by a shunt coil N, controls the movement of the carbons. When the lamp is not in use the carbons are in contact, and, upon closing the lamp-switch, the coil H drives the disc in the direction for raising the carbons, thus striking the arc. The coil N now becomes excited, causing the gradual slowing down of the disc, until the arc is of proper length, after which, as the arc increases in length, the disc is driven reversely and feeds the carbons down.

The carbons used in Excello lamps are provided with a continuous metallic core, which reduces the resistance of the carbons to a great extent.

The "Juno" flame arc lamp, by Messrs. Johnson and Phillips, embodies an ingenious feed mechanism, seen in Fig. 629. The carbons C_1 C_2 are fixed in holders H H, which are carried by, but insulated from,



629.—JUNO FLAME LAMP.

cross slides S S. The slides are connected together by the pin and slot connection shown, and move up or down over the guide rods R R. It is thus seen that the carbons must move equally and together when feeding takes place. The carbon C_1 rests upon an abutment A, which is simply a bent copper rod secured by a set screw in the wall of a brass cup B surrounding the carbon tips, the cup being designed to protect the flame arc from draughts. The feed is regulated by an angular gravity member F whose axis is at the point G, and which carries a collar K engaging the carbon C_3. The movement of the piece F, which is limited in the downward direction by an adjustable set screw, is controlled either by a solenoid or by a hot series wire W, as shown. When no current passes through the lamp, the tension of the wire W is adjusted by the screw L, so that the piece F is raised and the carbon tips are held in close contact. The wire W, upon the passage of a current, becomes heated, and slackens under the resulting expansion, the piece F is thus permitted to drop and to strike the arc by means of the collar K, which pushes the carbon C_2 away from the carbon C_1. The wire W is flattened in the middle to enable it to cool quickly, and, therefore, as the arc lengthens and the current decreases in strength, the wire cools and contracts and draws the carbon tips closer together. An arrangement not shown, also provides a magnetic deflection by employing part of the iron construction as a magnet core.

The flexibles necessary for connecting the terminals with the carbons are omitted from the figure.

MAGAZINE LAMPS.

The reasons for the short life of the carbons used in flame lamps have been referred to already, and a description will now be given of a flame lamp constructed to burn cheap carbons, but which nevertheless burns for forty to fifty hours without retrimming. The lamp in question is known as the "Oriflamme," and is made by Messrs. Oliver & Company, Woolwich. The Oriflamme exhibits great ingenuity in almost every particular, and is illustrated in Figs. 630 to 633. The long burning period of this lamp, even with cheap "effect" carbons of small diameter, is attained by the use of flat receptacles or magazines. Fig. 630 (*g*) shows the magazines edge on, and in this figure it is seen that the magazine on the right is pivotally suspended at *h* from an insulated bracket, whereas that on the left is not. Fig. 631 shows the right hand or pivotal magazine in side elevation, and in Fig. 632 a magazine is shown detached and with part of its wall broken away. The carbon whose end is within the delivery aperture, is pressed into contact with a feed chain *c*, which runs over pulleys upon a shaft *d*. The cross shaft extending between the two magazines carries a ratchet wheel *e*, which is intermittently driven by a pawl *t* in connection with the armature *q* of a magnet *p*. The arc is under the immediate control of a compound solenoid *k*, wound with a large number of turns of fine wire in shunt, and a few turns of thick wire in series with the arc. The core *l* of the solenoid is hooked to a dash pot *o* to prevent spasmodic movements, and operates upon the free end of a counterweighted lever or cradle *m* with fulcrum at *n*. A link *j*, Fig. 631, connects the lever *m* with a small bell-crank lever, also marked *j* in Fig. 630, and thus, when the solenoid *k* is not active, the core *l* and right-hand arm of the lever *m* descend, and the little bell crank lever is rocked so that its vertical arm pushes the right-hand magazine away from the fixed magazine. When current is turned on, the shunt winding sucks up the core, and the magazine *g* swings towards the left-hand magazine until the carbon tips meet, when the core *l* at once descends and separates the carbons, thus striking the arc. When the arc grows too long and the coil *k* again sucks up the core *l*, the opposite arm of the lever *m* is lowered and pushes

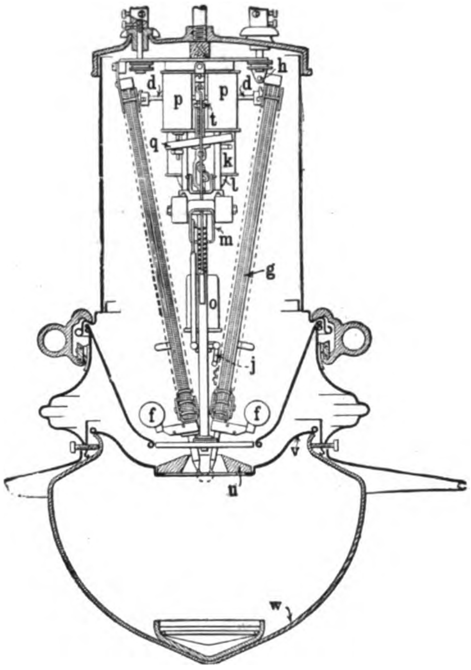


FIG. 630.—SECTION OF ORIFLAMME LAMP THROUGH MAGAZINES.

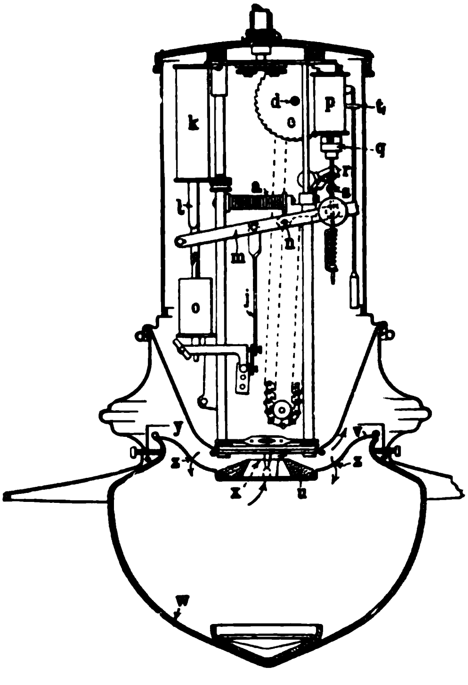


FIG. 631.—SECTION OF ORIFLAMME LAMP SHOWING MECHANISM.

down the link *s* and armature *q* through the medium of the coil spring, at the same time tilting a little glass vacuum bulb containing sufficient mercury to make contact, when the bulb is tilted far enough, between two terminals in the circuit of the coil *b*. When such contact is made, the coil *p* draws up its armature *q*, and the latter, by means of its pawl *t*, turns the ratchet wheel, causing the chains *c* to feed their respective carbons downwards. The armature *q*, in rising, restores the tube *r* to its original position, and the circuit being broken the armature *q* flies back, and the tube is again tilted to make circuit, the result being a step by step equal and positive feed of the carbons for so long as the core *l* remains sufficiently raised. The large aperture *x* in the porcelain economising reflector *u*, enables the combustion gases of the carbons to escape freely to the isolated space *y* above the plate *v*, so that deposits of carbon on the globe are avoided. The air being introduced through holes *z*, the lamp is well ventilated, the arc at the same time not being subjected to undue draught. The arc is deflected by a coil *a* which magnetises the two upright frame members seen in Fig 631, terminating just above the arc. The carbons are prevented from moving out of the magazines, unless positively fed out, by the weighted clutches *f*. The various circuits are clearly represented in diagram in Fig. 633, and will be easily understood from the foregoing description. The counterweight on the lever *m* can be varied to adapt the lamp to different voltages.

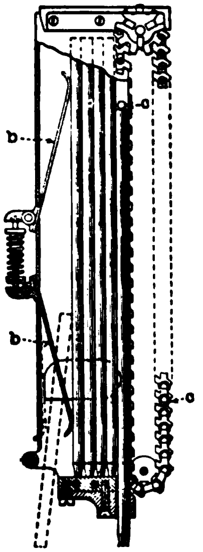


FIG. 632.—MAGAZINE OF ORIFLAMME LAMP.

ENCLOSED LAMPS.

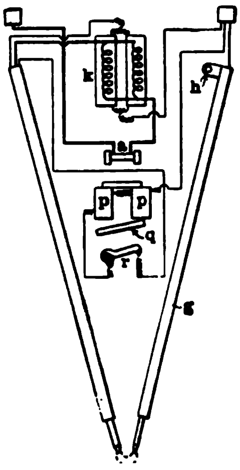


FIG. 633.—FEED MECHANISM OF ORIFLAMME LAMP.

The pioneer of the modern enclosed arc lamp is that known as the "Jandus," and the lamp illustrated in section in Fig. 634 embodies the various improvements which have been added one by one to the original Jandus arc lamp. Only the upper carbon *a* is fed, the lower carbon *b* being fixed. The holder *c* has an annular packing channel for receiving the bottom edge of the globe, and the top edge of the globe is held tight against the reflector *e* by the strong spring pulling on the left hand rod. Just beneath the reflector there is fixed a cap casting *f*, and these two parts enclose a dead air space which assists in keeping any outside air from the arc. Current is fed to the upper carbons by clutch or bearing rings which are carried upon a conducting ring, and bear upon the carbon. The feed of the upper carbon is governed by a single solenoid *h* arranged co-axially with the carbon. This solenoid is iron-cased, and the core *j*, is coned at its upper end, in order that there shall be a more uniform pull throughout its travel. To the core is pivotally connected a lever *k*, having a fulcrum on the bracket *l* which connects with the rod *m* of a dash pot on the right-hand side. A tube *n* is connected to the core *j*, and surrounds the upper carbon *a*, the lower end of the tube *n* being received in a guiding tube *o*. The upper carbon passes freely through the core, and at its upper end is received in a sheath sliding within a fixed tube *r*, while the lower end passes through a tilting washer clutch *p* pivoted to the lower end of a link rod *s*. Spring *t* operates to tilt the washer *p* to cause it to grip the carbon when the solenoid core raises the tube from the washer. The action of the lamp is quite simple; when the current is switched on, the core *j* is raised by the compound-wound coil; the washer *p* becoming tilted grips the carbon and, being raised also, lifts the carbon and strikes the arc. When the arc is too long and the pull of the coil is insufficient to maintain the core in its raised position, the core descends gradually, and finally the washer *p* becomes horizontal, and feeds the top carbon. These lamps burn for 200 hours without retrimming. The comparatively great weight of the core prevents any pumping.

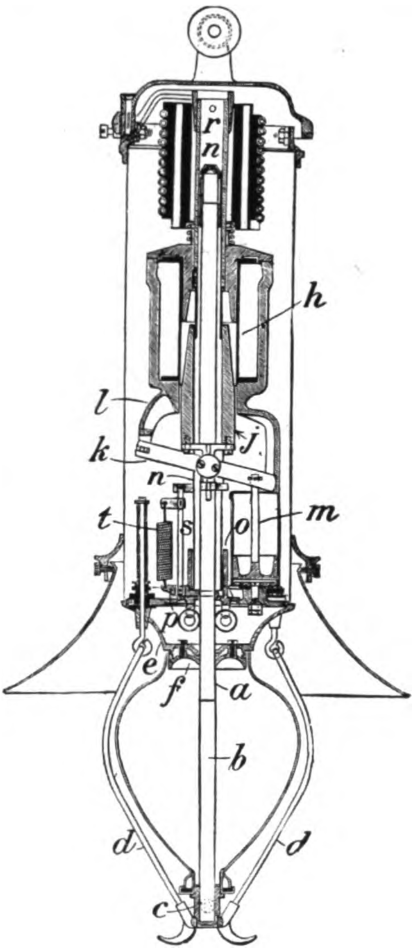


FIG. 634.—SECTION OF JANDUS LAMP.

PHOTOMETRY.

The true art of photometry consists in comparing the relative values of two sources of light; but while the process may sound simple, it is a matter of extreme difficulty unless they be practically identical in nature and differ only in power. The total light emitted from any given source is made up of components of almost every imaginable colour in the spectrum, from the red up to the violet. Infra red or heat rays and ultra violet or actinic rays are also emitted. At present we are concerned only with those rays which lie within the range of ordinary vision. The quality or tone of any particular source of light depends upon the presence or absence of rays of any particular colour, and also upon the relative strengths of the colours which are present. The eye is very variously affected by different colours, and the result is that of two sources of light which some experimenter may say are equal, as a result of his photometric test, one will give a general impression of being a much stronger light than the other. There can be little doubt, in the author's opinion at least, that the colour which produces the greatest light effect for general illumination is a yellow, and that a yellow not too near the green in the spectrum. A very good proof of this is to be found in the streets of London, where very often one may find two neighbouring shops, one of which is provided with ordinary arc lamps, and the other with flame lamps. The ordinary arc lamp produces a somewhat sickly bluish light, while the enclosed lamp gives a light of an even ghastlier hue of a very pronounced blue character. One has only to walk by a couple of shops so lighted, to feel in passing from the zone of the yellow lamps to that of the ordinary lamps that one is passing from a brilliantly lighted area into one of quite dim illumination. This will be the case even when some four open-type lamps are pitted against a couple of good flame lamps. The light from the three types of lamp mentioned above (as measured with a photometer at various angles) is plotted in Fig. 635,* in which the curves *a*, *b*, and *c*, show the candle power of an enclosed, an open, and a flame lamp respectively. The effect upon the naked eye would probably be more pronounced than the curves indicate.

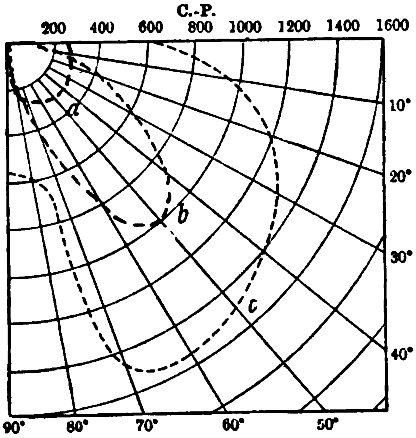


FIG. 635.—CANDLE-POWER CURVES OF ARC LAMPS: (*a*) ENCLOSED, (*b*) OPEN, (*c*) FLAME.

The number of photometers that have been from time to time invented is extraordinarily large, but they must clearly all depend upon the comparison between two illuminated surfaces, one of which is illuminated from some standard source of light and the other from the lamp or source which is to be tested.

STANDARDS OF LIGHT.

The selection of a standard is a matter of some difficulty. For many years the standard adopted at the gas-testing stations under the control of the Board of Trade was a standard candle. The candle consisted of pure spermaceti, and under standard conditions consumed 120 grains per hour. It was, however, soon found that the prescription of the material and of the rate of its burning is not sufficient to insure a uniform light. Other standards that have been suggested are usually arranged to burn some liquid fuel whose composition can be accurately determined at a definite rate, the fuels used being colza oil, pentane, amyl acetate, benzene, ether, ethylene or naphthalene. Various forms of standard lamps burning gaseous fuel have also been introduced from time to time, such as the one recommended by the American Institution of Electrical Engineers, in which defined volumes of acetylene and hydrogen are first mixed and then burnt in pure oxygen. A further standard on which innumerable experiments have been made, is the Violle standard, viz. the light emitted from a square centimetre of surface of molten platinum at its freezing point.

The Amyl-Acetate Standard.—A standard lamp of great constancy, but of low intensity, has been devised by Von Hefner-Alteneck, using as a fuel amyl acetate. (Fig. 636.)

The purity of the amyl acetate has but small effect on the intensity of the light, but the condition of the atmosphere produces a considerable variation, the light declining in a vitiated atmosphere. After the lamp has been burning about ten minutes it has attained its normal intensity, and may be used for measurement. It has been adopted as a standard in Germany by the Society of Gas Engineers.

---

* Adapted from *Electrical Engineering*, July 4, 1907.

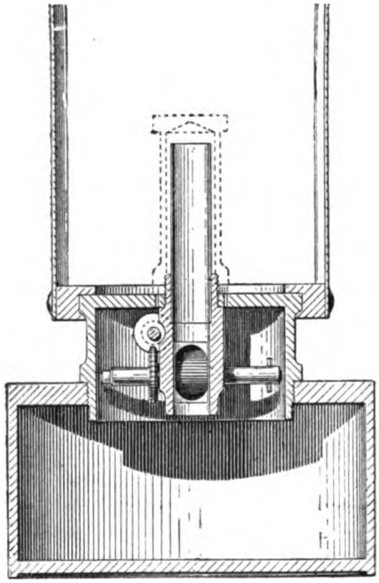


FIG. 636.—AMYL-ACETATE STANDARD OF VON HEFNER-ALTENECK.

The Harcourt 10 *Candle-power Standard.*—This lamp is shown in Fig. 637, and is an air-gas lamp. The reservoir R is about two-thirds full of pentane, the height of which may be seen through the small window W. The vapour passes through the tube T to the argand burner. The top of the flame is in the chimney A in which there is a mica window so that the flame may be adjusted to the correct height. The chimney is surrounded by an outer tube C, and the air between the two being heated, rises and passes along D, down E to F, and thence to the burner, where it mingles with the pentane vapour.

The distance between the burner and the bottom of the chimney A is adjusted before lighting by means of a gauge, and the flame is screened by S, in which is an opening large enough to allow of the whole flame being seen.

The pentane lamp is easier to work with than the amyl-acetate lamps, and as at present made gives fairly satisfactory results.

PHOTOMETERS.

The comparison between various sources of light is made by comparing the illumination by them of similar surfaces. The law of inverse squares is assumed (it is easily proved for *points* of light); it follows from this that if two surfaces are equally illuminated, the intensity of the source varies directly as the square of its distance from the surface.

The Bunsen Grease-Spot Photometer.—The simplest form of photometer, and one which is quite suitable for comparing lights of the same tint, is that known as the "grease-spot" photometer. A sheet of tissue paper on which has been made a spot with some colourless grease or oil, is set up vertically on a carrier which moves over a graduated bar between the two sources of light which it is desired to compare. Thus the paper is illuminated on one side by source A, and on the other side by source B. The observer watches one side of the sheet, say that illuminated by B, and moves it about

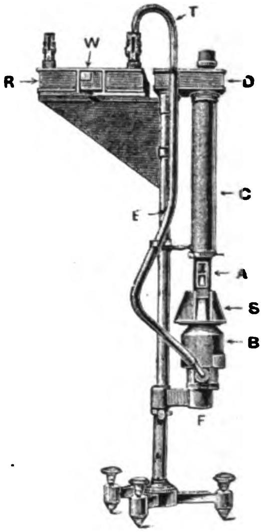


FIG. 637.—VERNON-HARCOURT'S 10-CANDLE POWER PENTANE STANDARD.

until the grease-spot is invisible. When this is the case, the light transmitted through the grease-spot from A, is equal in intensity to that reflected by the paper from B. The distances of A and B from the screen are now noted. The experiment is repeated, the other side of the paper being watched, and the distances again noted, the average of the two experiments being taken. If the amount of light lost in transmission through the grease-spot were equal to that lost in the process of reflection, it would not be necessary to take a reading using each side of the screen, but as this is not usually the case, it is essential to do so.

The Lummer-Brodhun Photometer. — A more complicated variety of photometer, but one which has been much used, especially for lights of the same tint, is the Lummer-Brodhun, a diagram of which is shown in Fig. 638. S is a magnesia slab, P_1 and P_2 totally reflecting prisms, Q P a special Lummer-Brodhun prism, and T an observing telescope. The paths of the light from sources A and B are clearly indicated.

Thus, on looking through the telescope, a disc is seen, the centre of which is illuminated from A, and the outside annular space from B. The distances are adjusted to give a uniformly illuminated disc, and the comparative intensity of the lights worked out in the ordinary way.

Simmance-Abady.—In this photometer a flickering effect is produced by replacing the fixed screen of the ordinary photometer by a rotating wheel, of perfectly white material, with curiously bevelled edges. The edge of the wheel produced by the bevelling, moves from one side to the other. Fig. 639, shows the wheel in four positions. One light is placed on each side of the wheel, in the line of its axis, and reflection takes place from the sloping surface of the bevel. All that is necessary is to adjust the distance of the wheel between the lights so that there is no observable flicker. The results obtained by this and other photometers of the flicker type are independent of the colour of the field.

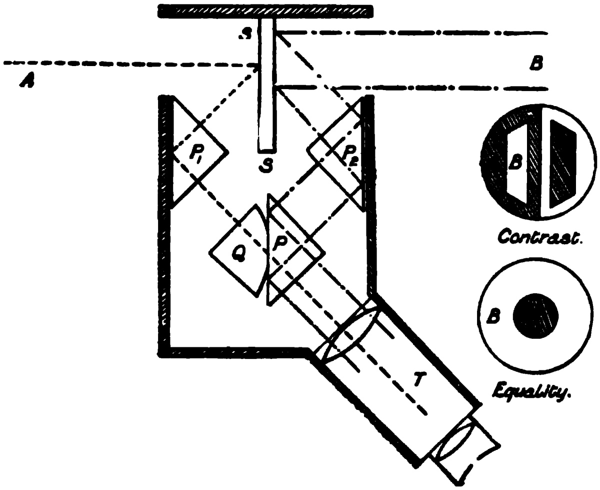


FIG. 638.—LUMMER-BRODHUN PHOTOMETER SCREEN.

THE PURKINJE PHENOMENON.

The ultimate arbiter for all photometric measurement is the human eye, since photographic and other chemical methods, or heat methods, are affected by radiant energy of such wave lengths as cannot be felt by the eye, and which cannot therefore strictly be called light. Photometry is thus a measurement of the power of a luminous body to excite the optic nerve. There is a minimum stimulus capable of exciting the nerve, and this is called the threshold stimulus, and Fechner showed that the effect of larger stimuli is proportional to the logarithm of the energy of the stimulus. The degree of proportionality depends upon the colour, *i.e.* the wave length of the light.

The source of all the trouble arising from the differences in colour of sources of light to be compared is to be found in this effect first investigated by Purkinje. For example, let two different-coloured lights, a red light and a green one, say, be balanced on a photometer as closely as possible. Now let the lamps be moved each to half the distance at which it formerly was from the photometer. The strength (or intensity) of the light falling on the photometer from each will have been quadrupled, but balance on the photometer will be quite upset, and the red side will appear to be much brighter than the other. On the other hand, if they had been moved to a position further from the photometer, the red would have lost more light than the green, and the green would have become the brighter. From this it follows that the rate of change of sensation in the eye produced by the red light is greater for a given change of stimulus than is the case with green.

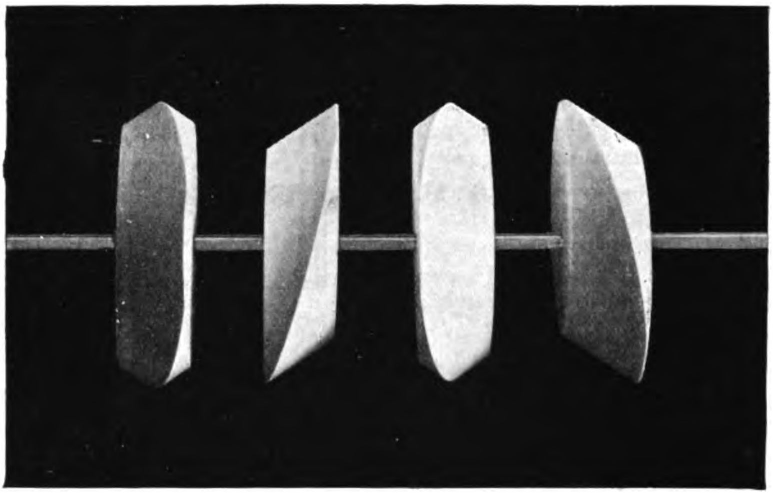


FIG. 639.—SIMMANCE-ABADY PHOTOMETER WHEEL.

In practical photometry the most important quantities to be determined are the mean spherical candle power and the illumination at the street or floor level at varying distances from the lamp. Limits of space prevent further reference to such measurements.

CHAPTER II.—INTERIOR WIRING.

CABLES FOR INTERIOR WIRING—LOADING OF CONDUCTORS—JOINTING OF SMALL CABLES—SYSTEMS OF WIRING—FITTINGS FOR ELECTRIC LIGHTING—WIRING FOR POWER PURPOSES—MOTOR STARTERS—SPEED REGULATION—PRECAUTIONS AGAINST FIRE RISK—PRECAUTIONS AGAINST SHOCK—REGULATIONS OF AUTHORITIES—TESTING.

CABLES FOR INTERIOR WIRING.

THE conductors used for house wiring are either solid copper wire, or, in the case of larger conductors, a number of wires stranded together, tinned on the surface in order to prevent the insulation with which they are in contact from corroding them, and enclosed in a layer of insulating material, such as vulcanised indiarubber or its equivalent. Upon this insulating material is wound one or two layers of insulating tape, and the whole is then braided over and waxed to protect it from moisture. The sectional area of any copper conductor should not be less than that of a No. 18 S.W.G. wire, and single wires should not be used in sizes greater than No. 14 S.W.G., as wires smaller than No. 18 are too tender, and would be liable to accidental fracture, even inside the covering, while being installed, and wire larger than No. 14 is apt to be damaged if bent at too sharp an angle.

Conductors of greater sectional area than No. 14 S.W.G. should consist of smaller wires stranded together to form a cable; in this way greater flexibility is obtained, and for this reason it is good practice to use none but stranded conductors in house wiring.

For suspending lamps from ceilings and similar purposes specially flexible conductors are used; these consist of a large number (generally from 60 to 120) of fine wires of about No. 40 S.W.G. stranded together, bound with a layer of cotton, insulated with vulcanised rubber, wound with two more layers of cotton and, lastly, braided. These conductors are generally twisted together in pairs, and are extremely flexible; their use, however, should be avoided as much as possible, since they are not mechanically well protected and are a constant source of trouble if subjected to rough usage. For wiring fittings, etc., where the ordinary wire is too bulky to be used inside the small brass tubes of the fittings, a special "electrolier" or "fittings" wire is manufactured which is well insulated and fairly flexible, but relies mainly upon the fitting for its mechanical protection. Ordinary flexibles should in no case be used for this purpose.

LOADING OF CONDUCTORS.

A rule was framed at an early date by the fire insurance companies that no conductor should carry more current than 1,000 amperes for each square inch of cross section, and that rule still exists in some specifications, and is used to some extent to-day; it is, however, obviously a bad one, for the current which a conductor will carry safely is limited only by its temperature rise, and though this is inversely proportional to the area, the cooling surface in small wires is much greater in proportion to the section than in large ones, and for this reason small wires can carry more current per unit of cross-sectional area than large ones for a given rise of temperature. It is customary now, therefore, to allow very high current densities, up to nearly 3,000 amperes per square inch, in very small wires, but only about 750 amperes per square inch in large ones, as these densities are found to give about 20° F. rise in temperature. The relation between area of conductor and current density allowable is given in the form of a curve in Fig. 640. The maximum current which any conductor insulated and laid in the ordinary way should carry has been prescribed by a Committee of the Institution of Electrical Engineers and is given by the formula :

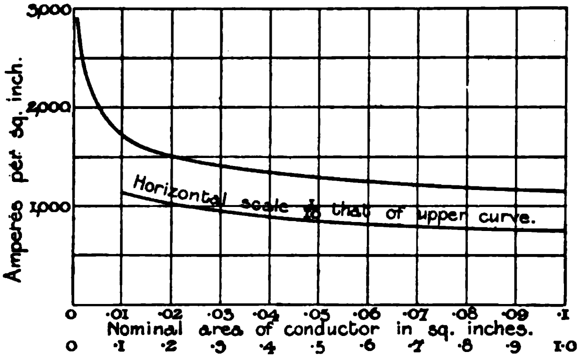


FIG. 640.—CARRYING CAPACITY OF CONDUCTORS.

$$\text{Log } C = 0{\cdot}82 \log A + 0{\cdot}415$$

or $$C = 2{\cdot}6\, A^{0{\cdot}82}$$

where C = current in amperes

A = sectional area in 1,000ths of a square inch.

In places where the external temperature exceeds 100° F. (37·8° C.) the maximum current allowable will be less and may be calculated from the formula :

$$\text{Log } C = 0{\cdot}775 \log A + 0{\cdot}301$$

or $$C = 2\, A^{0{\cdot}775}$$

In practice, however, the allowable current would be taken from a table such as that published by the Institution of Electrical Engineers.

JOINTING OF SMALL CABLES.

The greatest care must be exercised in the jointing of wires and cables, for unless all the joints of an installation approach very nearly to perfection, they will impair its insulation resistance and efficiency to such an extent as to render useless the greatest care in workmanship and choice of materials which may have been expended on other parts of the system.

Single wires are jointed by baring back the insulation of the conductors sufficiently to allow of about an inch to an inch and a-half of bare wire being twisted together. The braiding and tape should be stripped off further back than the rubber since they promote surface leakage from the bare wire. The twisted wires are soldered with a bit, care being taken that no rough edges are left on the joint.

The only fluxes which may be used for this soldering are resin and one of the pastes specially prepared for electrical work, and any excess of flux which remains after the joint is soldered should be carefully wiped off. Acid fluxes should on no account be used, as they are liable to corrode the wires.

Stranded cables are jointed by separating the strands for a short distance and spreading them out, then cutting out the middle strand and bringing them together as shown in Fig. 641*a*, the wires of each cable are then neatly wrapped round the one to which it is to be connected, as shown in Fig. 641*b*, and the whole soldered into a solid mass. "T"-joints in single wires may be made by simply twisting the end of the branch wire round a length of bared wire, but a more usual method is to make a "running" joint, such as is shown in Fig. 642, and these are generally more satisfactory.

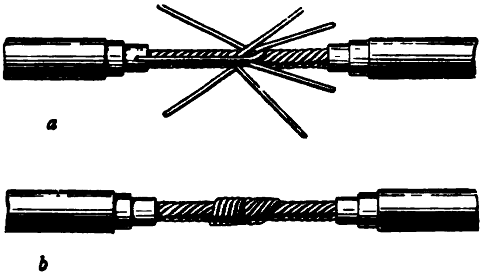


FIG. 641.—STRANDED JOINT.

In the case of larger cables a T-joint may be made by separating the strands of the branch cable and twisting them round the main cable, half in one direction and half in the other, as shown in Fig. 643, but joints in moderate sized cables may with advantage be made by means of special brass or gun-metal clamps, or by means of junction boxes.

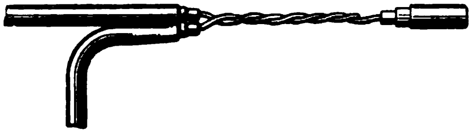


FIG. 642.—RUNNING JOINT IN SINGLE WIRE.

The jointing of large cables is a trade in itself, and the methods employed are discussed in Section X.

The soldered and cleaned joints are insulated with pure rubber strip, the strip being wrapped round so that each turn overlaps half of the preceding one, and it is carried well on to the rubber of the cable insulation from which the braid and tape have been stripped at each end of the joint. Three layers of pure rubber are laid on and rubber solution may be applied thinly over the outermost. Its use is, however, of questionable value. Waterproof tape is applied over all to complete the protection. Where the conductor is exposed at lugs or terminals it should be treated in a similar manner. The tapes when applied should be drawn as tightly as possible without fracture, and the diameter of the finished joint will then be only slightly greater than that of the original cable, while its insulation resistance will be very high. When "taping up" the running joint mentioned above special care should be taken that no part of the joint is left uncovered where the wires lie parallel, and that no flux remains on the wires at that point.

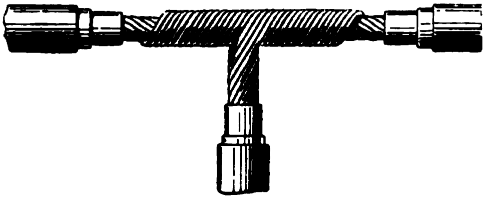


FIG. 643.—T-JOINT IN STRANDED CABLE.

The practice of cutting out several strands of a conductor to make it enter a terminal or lug of inadequate size is liable to be a source of trouble, especially in the case of soldered lugs, as overheating may occur when the conductor is heavily loaded, which, by melting the solder, is liable to cause a short circuit, or, in any case, to damage the insulation.

Joints of any sort are a source of weakness, and in order to avoid them as much as possible, "looping" is commonly employed. Figs. 644 (*a*) and (*b*) show two circuits, one of which is wired with joints and the other "looped." The method has advantages over that in which soldered joints are made, as all connections are accessible, and if heating should occur at such points they are generally surrounded by incombustible material. In some cases the practice of looping, rigidly carried out, would lead to the use of an excessive amount of wire. Installations may, it is true, be carried out by looping entirely without soldered joints, but they are expensive, and for ordinary purposes the method is only used where conditions lend themselves to its adoption.

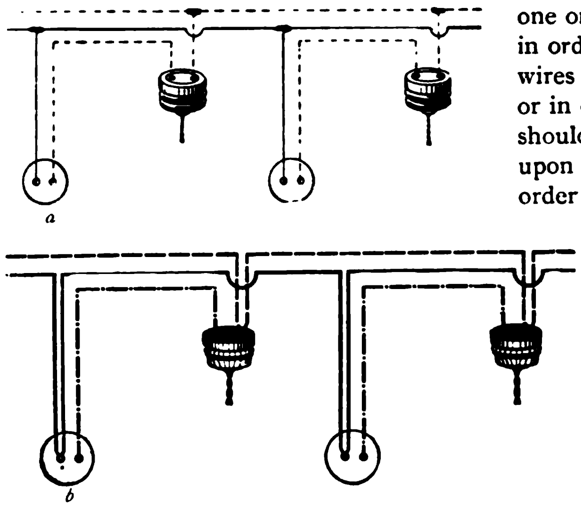


FIG. 644.—JOINTED AND LOOPED CIRCUITS.

SYSTEMS OF WIRING.

The majority of the wiring in this country is done on one of two systems, that is, the wires are either enclosed in wooden casing or in steel tubing. Other systems are the lead covered, in which case the protecting covering is attached to the wire itself, and that in which wooden or porcelain "cleats" are employed, and the conductors stretched between them. The wood casing system is the oldest and still the most general system, though the superior properties of steel tubing as a protection for the wires are fast bringing that system into favour, especially in large towns where the special fittings necessary are readily obtainable.

Wood Casing.—In the wood casing system lengths of casing, such as shown in Fig. 645, are fixed in position on the walls or elsewhere, and the wires laid in the grooves. "Capping" is then carefully screwed on top, thus keeping the wires in position and protecting them.

Casing should in all cases be treated with one or two coats of paint or shellac varnish in order to render it damp proof. When wires are laid in wood casing under floors, or in other concealed places, their presence should always be indicated by clear marks upon the floor boards or other covering, in order to prevent nails, etc., being driven into them, and to assist in locating faults if they should occur.

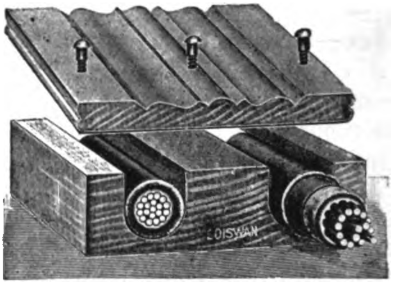


FIG. 645.—CABLE IN WOOD CASING.

Steel Conduit.—In the steel conduit system the wires are enclosed in steel tubing throughout their entire length, being, as a rule, threaded in as the tubes are erected, though it is a somewhat better plan to erect the tubes first and then draw the wires in through suitable junction and inspection boxes provided for that purpose, since the wires are not so liable to become damaged by workmen employed on the same building at the time of the erection of the tubes. Also, since the tubes are generally erected before the walls and ceilings of a building are plastered, it is advisable to allow them to become thoroughly dry before introducing the wires (in which operation a little French chalk blown into the tubes will be found materially to assist).

Several classes of tube are manufactured, two of which are shown in Fig. 646; *a* shows a piece of plain steel tubing and *b* a similar tube provided with an interior coating of insulating material.

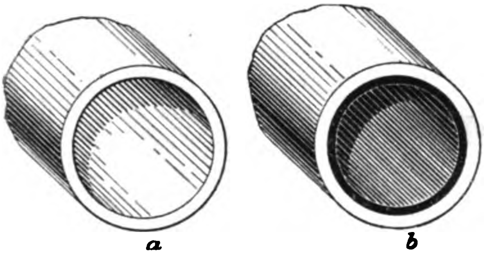


FIG. 646.—PLAIN AND INSULATED TUBE DUCTS.

Lengths of tubing are connected by means of "sockets" into which the end of the tube either fits tightly, or in the case of water-tight tubing, is screwed. Bends and curves are followed, and T-junctions, etc., made by means of special fittings, some of which are illustrated. Many special forms of connections are now made in which the necessity for screwing the steel conduit to make a water-tight and electrically continuous joint is obviated.

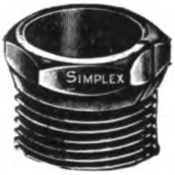


FIG. 647.—SPLIT GRIP FOR TUBE.

The contact nipple illustrated in Fig. 647 is a split screwed bush, which when screwed home into the fitting, grips the tube, from which the enamel has been scraped off for a short distance.

Another device for ensuring electrical continuity, made by the General Electric Company and illustrated in Fig. 648, is useful; one of its applications is shown.

Fig. 649*a* shows a ceiling rose wired on the looping back principle and mounted direct upon a special Simplex fitting, while Fig. 649*b* shows Simplex conduit attached to a steel girder, the method of fixing being clearly seen.

In wiring with steel tubing, wires of opposite polarity are bunched together in the same tube, no attempt being made to keep them separate; indeed, it is very important that cables of opposite polarity carrying alternating currents, and especially if of high frequency, should *not* be placed in separate steel tubes running parallel to each other, because if these conditions exist, the circuit will act as a choking coil of which the tubing is the iron core, and a serious drop in volts will be the result.

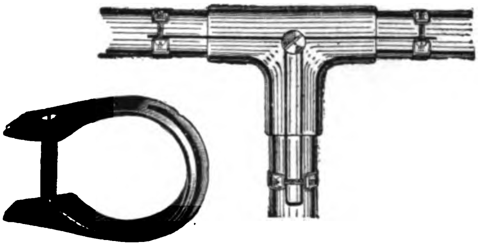
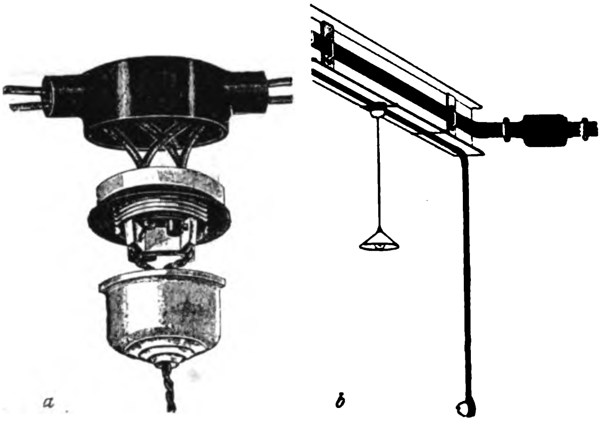


FIG. 648.—EARTHING CLIP FOR TUBING AND ITS APPLICATION.

The steel conduit system has many advantages over the wood-casing system. It is non-inflammable, and can be made water-tight, and is therefore suitable for damp positions and places where there is much moisture in the air. It also forms a much stronger mechanical protection for the wires.

The system, however, if properly carried out is more expensive than the wood casing, and cannot with anything like equal ease and promptness be adapted to suit local conditions unless a large and varied assortment of bends, junction boxes, T-pieces, etc., are kept in stock; and the contractor is sorely tempted, in order to save time and money, to improvise for himself on the spot for use in obscure places those fittings which may at any time be wanting, with the result that the system is frequently installed in an incomplete manner, which militates largely against its efficiency, and generally leaves it also non-continuous to earth.



. FIG. 649.—CONDUIT FITTINGS.

Lead covered.—Another system of wiring is that in which the wires are all covered with a lead sheathing which, when cut at joints, etc., is again rendered continuous and watertight, and should at some point be connected to earth. The system is not used in its entirety to any great extent, but the wire is very useful for running in damp places, such as on outside walls where it may be placed out of harm's way.

Unprotected.—Yet another method of wiring is to support the wires at intervals on a porcelain insulator of some sort, the wire between such supports being clear of all obstacles. These supports may conveniently take the form of porcelain cleats, similar to that shown in Fig. 650, but another very simple method is that shown in Fig. 651, which consists of a small porcelain reel screwed up against the wall or other fixture.

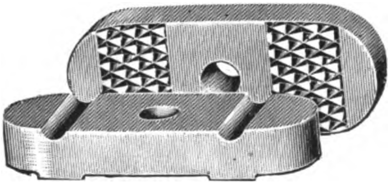


FIG. 650.—PORCELAIN CLEAT.

The wire is simply bound to the porcelain reel by a piece of copper binding wire.

In England such methods are only used in factories, workshops, underground railways, and the like, but in America and the Continent they are very largely used for house wiring, being indeed in some parts the standard practice.

Arrangement of Wiring.—The system on which wiring was done many years ago is known as the "tree" system; it is shown diagrammatically in Fig. 652, from which it will be seen that main cables were run through the building, being continually reduced in size as the current which they were required to carry was reduced. At each point where the cable was reduced in size it was of course necessary to place a fuse—which consists essentially of a piece of wire so proportioned that if the current it is carrying exceeds a certain limit it will melt and break the circuit (*see* below)—as the large fuses used for the main cable would not be sufficient protection for the smaller-sized cable.

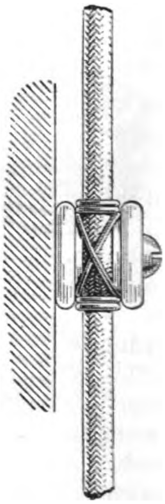


FIG. 651.—SURFACE WORK WITH PORCELAIN BUTTONS.

The result of this was that the fuses were scattered all over the building, often in almost inaccessible places, and in the case of a fuse blowing repairs were difficult even when the fuse which had blown was located, and another disadvantage was the risk of fire, which so many fuses involved.

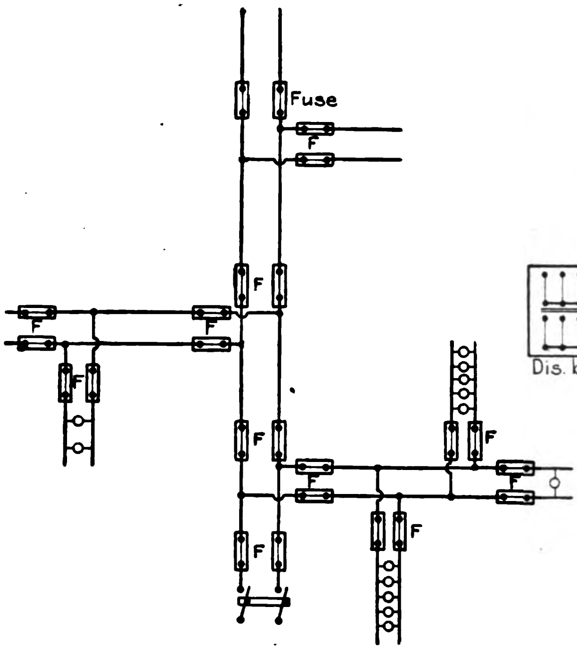


FIG. 652.—TREE SYSTEM OF CONDUCTORS.

The system which is now universally adopted is the distribution-board system. The supply is led in through main fuses, and from these, mains are run without reduction in size to distribution boards, which consist merely of a number of fuses grouped together in a suitable casing, and from these fuses smaller wires are taken to the switches and lamps, but no reduction is made in the size of the wires after they leave the distribution boards. These sub-circuits for lighting should be arranged so as not to carry more than 5 amperes on circuits up to 125 volts, or more than 3 amperes up to 250 volts. Fig. 653 shows the arrangement, the lamp circuits only being shown in one case.

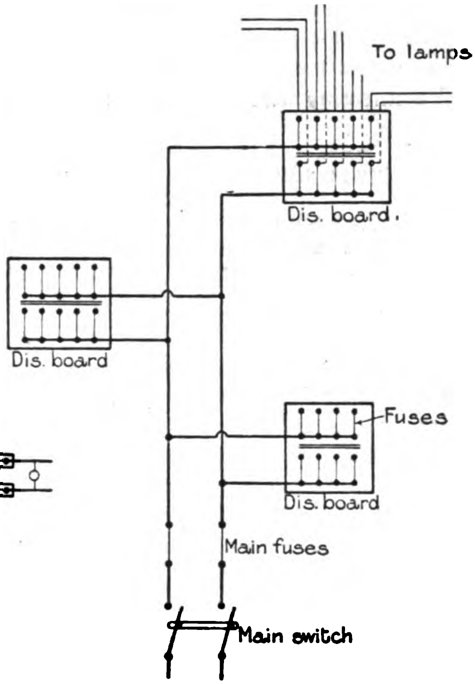


FIG. 653.—DISTRIBUTING-BOARD SYSTEM.

The ordinary circuit for an incandescent lamp consists merely of the switch and lamp in series across the supply circuit obtained from a distribution board or two fuses, all such circuits being placed in parallel, in those systems in which one main of the circuit is earthed the switch

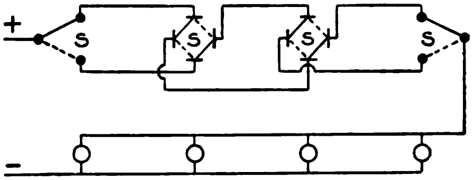


FIG. 654.—MULTIPLE SWITCH CONTROL.

should be placed upon the opposite main.

Fig. 654 shows the connections for controlling a group of lights from several switches, a special design of switch being made use of for the intermediate switches, two connecting wires also being necessary.

FITTINGS FOR ELECTRIC LIGHTING.

Fig. 655 shows a five-ampere switch of the pattern usually employed for house wiring, as made by Messrs. J. H. Tucker and Co. The chief requirements of switches are that their conducting parts shall have ample cross-sectional area and make good contact in order to prevent heating and consequent loss of energy, which may be considerable in a badly designed switch. They must not arc when the circuit is broken, must be incombustible, and their metal parts which are exposed must not be liable to come in contact with "live" metal; their bases are generally of earthenware, which, besides being a good insulating material, is moisture-proof. Ceiling roses should be so constructed that there is no possibility of a short circuit, and provision must be made for relieving the terminals of any mechanical strain due to the conductors.

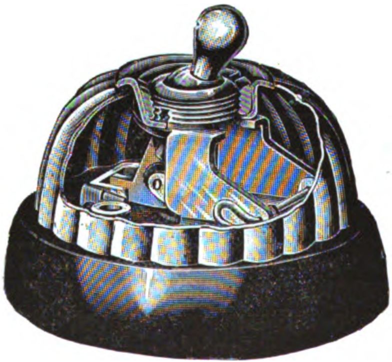


FIG. 655.—TUMBLER SWITCH.

Fuses, unless placed in distribution boards, are generally mounted on porcelain bases, and protected by a porcelain cover, which should be perforated for ventilation ; small sizes are arranged to blow when the working current is exceeded by 200 per cent. A fuse when carrying its normal current should feel warm to the touch, but not hiss when moistened. Care should, of course, be taken not to sustain shock when applying this test. For pressures below 125 volts both positive and negative fuses may be mounted on the same base, but for higher pressures separate fuses should be used. Hard metal is preferable to soft for fuses.

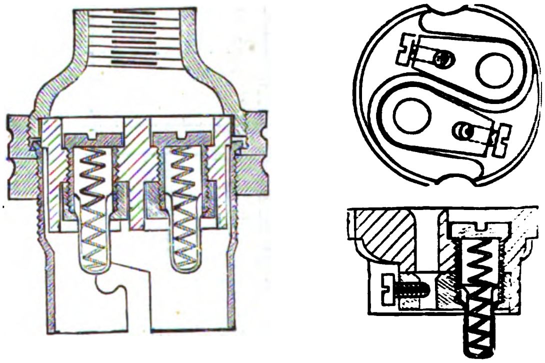


FIG. 656.—SECTION OF EDISWAN LAMPHOLDER.

Lampholders may be of many patterns, but the Ediswan bayonet cap pattern, with its **S** porcelain insulator, as shown in section in Fig. 656, is by far the most general in England, though the Edison screw socket lampholder, which is very common in America, is also used to a considerable extent here.

WIRING FOR POWER PURPOSES.

All motors of more than ⅓ horse-power should be provided with a switch and fuse, a circuit breaker, or a hand grip fuse on the one pole, and by at least one of these arrangements on the other, and these appliances should be readily accessible.

MOTOR STARTERS.

Motors must also be provided with some form of starting device, the main object of which is to prevent the motor from drawing too large a current from the supply mains when starting.

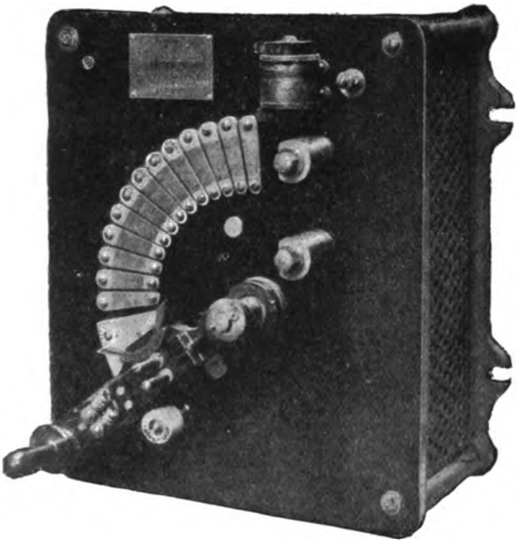


FIG. 657.—ADAMS MANUFACTURING COMPANY'S MOTOR STARTER, WITH RELEASE.

The form which this "starter" takes will depend upon the nature of the supply, upon the work for which the motor is intended, and upon the conditions imposed by the supply authorities. In practice they vary between wide limits, but space only admits of a few typical examples being given. A general requirement of all ordinary motor starters, however, is that they shall be fitted with a "no-volt release" in order that when the supply is cut off at the main switch or elsewhere. the starter may automatically go back to the starting position.

Shunt Motor Starters.—The starter for an ordinary continuous-current shunt motor is essentially a switch capable of first applying the full voltage of the supply to the shunt coils of the motor, and then supplying current through gradually decreasing resistances to the armature. Such a switch as made by the Adams Manufacturing Company, of Bedford, is shown in Fig. 657. The no-volt release is clearly shown above the terminals; it consists of a coil of wire wound upon an iron core and connected in series with the field across the supply voltage. The starting handle is held in the "off" position by a spring, but when moved up by hand against the tension of this spring to the "on" position, it is held there by the magnetic attraction of the no-volt release so long as the voltage of the supply is maintained, directly this fails, however, the magnetic pull ceases, and the starting handle flies back to the off position under the action of the spring.

The connections for such a starter are shown in Fig. 658, and it will be seen that upon moving the starting handle on to the first contact plate the full voltage is applied to the field windings through the no-volt release coil, and at the same time current is admitted to the armature circuit through the starting resistances. The motor then starts and generates a back E.M.F., which reduces the current flowing through the armature. As the handle is moved farther along the contacts the resistance in the armature circuit is reduced, but it will be evident from the diagram that the field current will have to flow back to the first contact through the resistances. When, however, the starting handle has been moved right over to the running position the brush marked X comes into contact with the "shunt button" S B, and so admits current direct to the field, while at the same time the short-circuiting brush upon the handle admits current direct to the armature. The armature current will be seen to traverse the winding of the overload release, which, if the current is excessive, lifts its armature (shown), and this, by means of extensions (which are not shown), short-circuits the no-volt release by bridging the two pillars connected therewith.

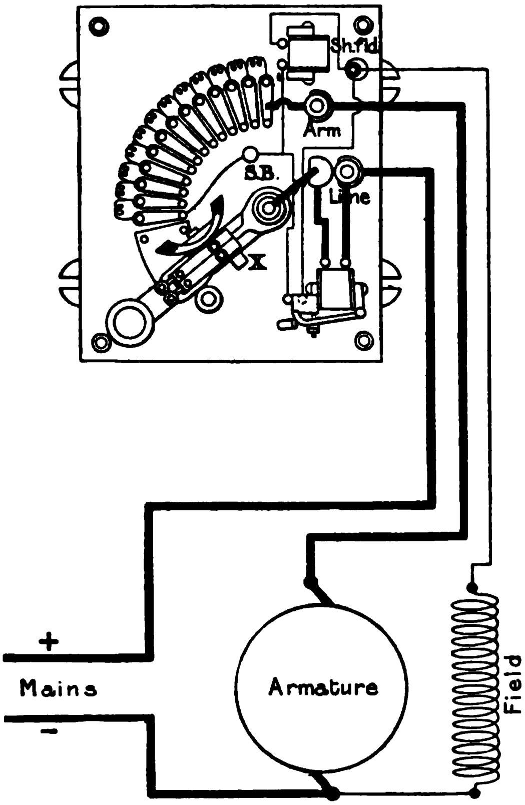


FIG. 658.—CIRCUITS OF SHUNT MOTOR AND ITS STARTER.

Theoretically, the handle should be moved over at such a rate that during the time that it is moving from one contact plate to the next, the back E.M.F. of the motor has increased sufficiently to reduce the value of the armature current from that allowed for starting the motor to the normal running current.

In Fig. 659 is shown the arrangement of a motor starting panel complete, with starting switch, no-volt and overload release, main switch, hand grip fuses and meters complete, as made by Messrs. Ferranti, Limited; the method of mounting and making the necessary connections is also indicated.

Series Motor Starters.—In starting a series motor a resistance is merely put in series with the motor in order to cut down the current at starting to a reasonable value, which may be twenty or thirty per cent. greater than the normal full load current, this resistance being gradually decreased as the motor runs up to speed. The starting switch should be provided with a no-volt release arrangement. Fig. 660 shows the arrangement, but without the no-volt release, which, if added, would have to be operated by a coil connected across the full voltage of the mains.

The elaborate starting and controlling apparatus used in connection with tramway motors will be treated of in Section XI.

Induction Motor Starters.—The apparatus necessary for starting an induction motor will vary according as the motor is of the wound rotor type or squirrel cage rotor type, and, of course, single-phase motors require special apparatus, some of which has been described in Section VII., Chapter VI., page 610.

The starting connections for use with a motor of the wound rotor type are given in Fig. 661.

The three-phase motor is connected to the line through fuses and a triple-pole switch. The slip rings of the rotor are connected each to one end of a resistance, the other ends of each of these resistance coils being short circuited by the arms of the starting handle.

As the motor runs up to speed, the resistance is cut out gradually by rotating the starting handle in a clockwise direction, until finally all the resistance is cut out and the slip rings are short circuited.

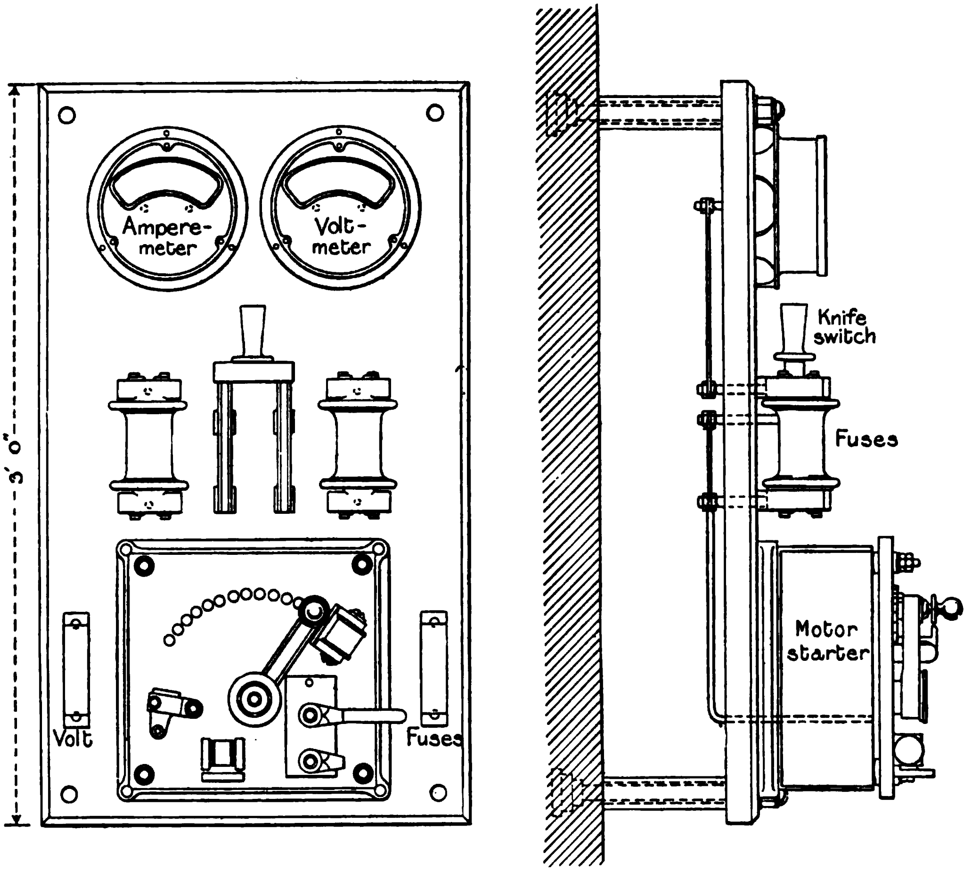


FIG. 659.—COMPLETE MOTOR SWITCH PANEL.

It will be remembered that both two- and three-phase motors are generally provided with three-phase rotors, so that the starting apparatus described for three-phase motors will usually do equally well for two-phase motors.

Coming now to induction motors of the squirrel cage rotor type, by the use of an auto-transformer (also known as a "compensator," or "economy coil"), in the stator circuit of the motor, a higher starting torque is obtained than would be the case without its use. The principle of the auto-transformer will be made clear by a reference to Fig. 662, which shows diagrammatically the connections.

A coil having been wound on a closed iron circuit, the terminals are connected direct to the mains, and the current that flows is a small lagging current such as the primary of a transformer would take. A tapping is made to a point in the coil, the position of which from one end of the winding bears to the whole length of winding the same proportion that the desired voltage bears to the main voltage. The apparatus to be served is connected to this point B, and to the end A above referred to. The apparatus, say the starting winding of a motor, now receives current from two sources. The winding lying between the points A and B is the seat of a voltage which, if A B be considered as part of the whole winding A C, is a back E.M.F. of self-induction ; but if the winding A B be considered by itself, the voltage is like the secondary voltage of a transformer. This winding therefore delivers current, driven by the induced E.M.F. to the apparatus, and the current flowing through the winding B C also traverses the apparatus. Thus at some one instant when the upper main is positive for the time being, the flow of current in the various parts will be as indicated by the arrowheads.

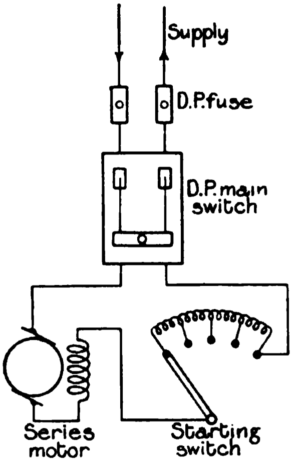


FIG. 660.—SERIES MOTOR AND STARTER.

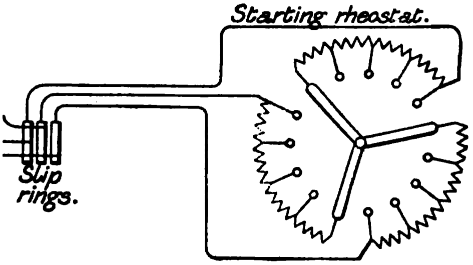


FIG. 661.—INDUCTION MOTOR STARTER.

The line voltage is applied across the terminals of the whole coil, while tappings are taken at different points along this coil and connected in succession to the motor terminals.

Oudin[*] gives the average performance of motors of American make with short-circuited rotors and compensators, approximately as follows :—

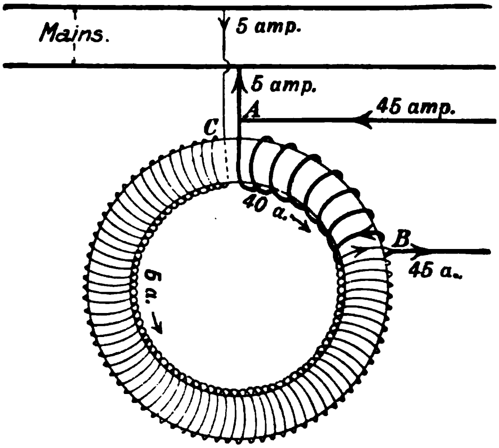


FIG. 662.—" AUTO-TRANSFORMER " OR ECONOMY COIL.

E.M.F.	Starting Current.	Starting Torque.
Per cent.	Per cent.	Per cent.
40	112	32
60	250	72
80	450	128
100	700	200

As compared with these results it should be remembered that with the wound rotor and the correct amount of resistance in the rotor circuit, it is possible to obtain at starting full load torque for little more than full load current.

Automatic circuit-breaking devices for

---

[*] Oudin, "Polyphase Apparatus and Systems," page 77.

alternating currents may be operated by means of alternating current relays, the action of which is similar to that of the induction instrument described on page 295.

Reversing Switches.—It is sometimes necessary that a motor should be capable of running in either direction, and for this purpose special switchgear is necessary. In reversing a continuous-current motor it is of course only necessary to reverse the direction of the armature current; the direction of the field current remains unaltered.

In order to reverse a three-phase motor, as we have already mentioned, it is only necessary to reverse one phase of the supply. Single-phase motors of the induction type if run up to speed in either direction will run equally well, but if of the split-phase class must be run up in whichever direction is desired, by reversing, if necessary, the connections of the starting winding; they are, however, practically never used for work where frequent stops and reversals are necessary, on account of their bad starting properties.

SPEED REGULATION.

The speed of continuous-current motors is generally controlled by one of the three following methods:—

(1) By inserting resistances in the field circuit;

(2) By inserting resistances in the armature circuit;

(3) By inserting resistances in both field and armature circuits.

The first is the most usual arrangement, a sub-divided high resistance, capable of carrying the field current, being included in the field circuit. This resistance, if equal to about half that of the shunt coil, will give about 25 per cent. speed variation, the speed being increased as resistance is introduced into the shunt circuit, and consequently, the field weakened; and since the torque is decreased as the speed is increased, the motor gives approximately constant power.

Fig. 663 shows a switch capable of starting, reversing, and controlling a motor, the small shunt contacts are easily recognised, while the heavy contacts for inserting resistance in the armature at starting are seen in the upper part of the panel.

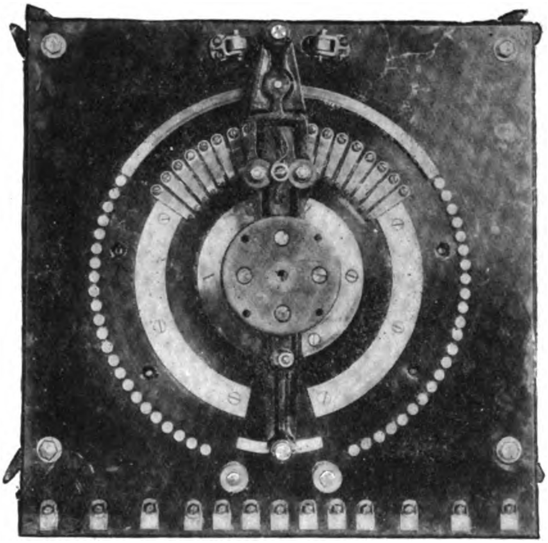


FIG. 663.—MOTOR CONTROLLING SWITCH.

The method in which resistances are inserted in the armature circuit is a wasteful one, but may be used for a motor working on a constant load; if, however, the load varies, the speed of the motor will vary inversely as the load, and consequently, the motor will not be under proper control.

For driving machines the speeds of which constantly require to be varied, the methods of speed variation above mentioned may be used, and give an excellent regulation, but the loss in the resistances is considerable, and renders it more economical, from a power consumption point of view, to obtain the speed variation mechanically in many cases. In a later chapter mention will be made of a system of distribution by which more that one efficient speed can be obtained from an ordinary motor.

For methods of varying the speed of induction motors the reader is referred to page 606 of Chapter VI., Section VII.

PRECAUTIONS AGAINST FIRE RISK.

From Lighting.—The risk of fire from an electrical installation will be negligible or considerable, according as the work is done well or badly, but in any case will be less than with any other form of lighting. One of the chief sources of danger are the fuses, which are often inadequate for the purpose for which they are used, with the result that when the fuse melts an arc is set up across the terminals which may ignite material in the vicinity; they should therefore have terminals an ample distance apart, and should be provided with some arrangement such as a porcelain bridge between the terminals for preventing arcing, and should also have an incombustible cover to catch the molten metal. Distribution boards should in all cases be lined with some non-inflammable material such as asbestos. Care should be taken to avoid gas pipes, and where it is necessary to cross them, to pack the casing or conduit containing the wires clear of the pipes. Where old gas fittings are converted for use with electric light, they should be entirely disconnected from the gas supply; combined gas and electric fittings are rapidly becoming extinct in England, though they are extensively used abroad.

Flexible conductors should not be used except where they hang freely in the air; when used in electroliers or table standards an insulating bush should be provided at all points of contact with the fitting. The cord grips where the "flexible" enters a lampholder should be carefully rounded, otherwise some of the strands will be eventually fractured there and, finding their way through the insulation, will short-circuit the conductors, and if the fuse is not rightly proportioned (which is not infrequently the case), the conductors, melting, will drop the lampholder and lamp and set fire to the insulation.

In damp places conductors must be contained in water-tight tubing, and in places where the tubes are liable to internal condensation means must be provided for draining them; if wood casing is used in damp places the conductor insulation, if faulty, sometimes becomes penetrated by the moisture, and so a current is set up between conductors of opposite polarity through the wet casing, which, becoming charred, offers less and less resistance until it results in sufficient heating to start a fire.

From Motors.—Motors must be securely fixed a sufficient distance from inflammable material, and their controlling apparatus must be so situated that it is not a source of danger itself through heat given off, and is not liable to damage either from damp or from mechanical injury. Unless motors are of the totally enclosed type they should not be placed within a foot, measured horizontally, or four feet vertically, of woodwork or other combustible material, and they should rest upon an incombustible material, such as cement, stone, or iron. If motors are mounted on or above wood floors, they should have a sheet of metal placed beneath them to catch any pieces of hot carbon or fused metal which might through any accident drop from the motor. Motors used in certain industries are also exposed to inflammable dust and gases. In such cases the motors should be either of the totally enclosed or the ventilated type, but if of the latter type must have all ventilating openings protected with fine wire gauze, or with perforated or expanded metal, and all commutators and slip rings must be completely enclosed. Holes through which bolts supporting a motor panel pass should be bushed with insulating material in order to insulate the panel as a whole from the supports, but all metal parts not intended to be "live" should be very thoroughly earthed.

PRECAUTIONS AGAINST SHOCK.

The shocks sustained from an ordinary lighting circuit of voltage up to 230 volts are generally of a quite harmless nature, unless received across the mains, for the simple reason that one is generally standing on a fairly bad conducting material, such as wood, stone, or dry earth, but they may in certain cases be highly dangerous, or even fatal. The only part of the installation with which the consumer comes in contact is the switch handle, and this should therefore be carefully insulated by some durable material, such as fibre or mica, and in addition to this, in cellars, bath rooms, and other inevitably damp places, the switch should be placed in such a position that it is impossible for a person to touch it when standing or having a hand in water, as this would make an excellent contact to earth.

It is, however, not always possible to place the switch out of reach, and in such cases an "all china" switch, such as the "Ediswan switch, shown in Fig. 664, should be used.

It is, of course, understood, that though in theory if both poles of a system are insulated, it should be possible to touch one pole with impunity, yet owing to leakage from the conductors, in practice one always sustains a shock unless well insulated from earth.

REGULATIONS OF AUTHORITIES.

A contractor when carrying out a wiring installation will have to comply with certain rules and regulations laid down by various authorities, chief among whom are those supplying the power, the consulting engineer or architect in charge of the work, and the fire insurance company with whom the building is insured.

The result is that he has to try and comply with several sets of rules at once, and since they not infrequently contradict each other, it is often impossible to do so. Much need has been felt for the adoption of a standard set of wiring rules, and those of the Institution of Electrical Engineers drawn up some years ago, and which are constantly revised, are now adopted by most of the insurance companies, though generally with certain additions of their own, and installations carried out in accordance with these rules are passed by them. The directions given in this chapter are based largely upon the I.E.E. rules, and will therefore be found to answer all ordinary requirements.

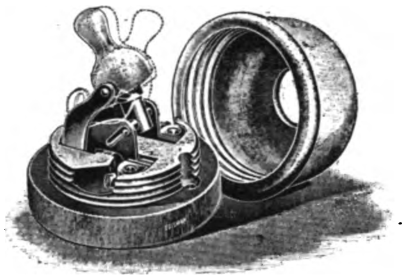


FIG. 664.—EDISWAN "ALL CHINA" SWITCH.

It is to be regretted that some of the insurance companies have formulated extremely elaborate and unnecessary rules for the prevention of fire risk from electrical supply, as this has led quite a large part of the public to believe that electric lighting is more dangerous from a fire risk point of view than gas or oil, of which perhaps no better contradiction can be given than the London Fire Brigade returns for the past year (1906), from which it appears that of the 3,843 fires occurring within the London County area that year, 2·7 per cent. were due to electrical causes, while 10·7 were due to gas.

TESTING.

The insulation resistance of an installation should be subjected to two separate tests before it is connected to the supply: it should be tested firstly, when the wiring is complete but no fittings or appliances are connected to it; and, secondly, when all lamps and fittings are in position and connected up.

The insulation resistance will vary with the size of the installation since, obviously, the more wiring there is connected to it, the greater will be the number of paths for leakage, and consequently, the lower the insulation resistance. The rule fixed by the Institution of Electrical Engineers is that when tested without fittings, etc., the resistance between the conductors of the whole or any part of the installation and earth must not be less in megohms (*i.e.* millions of ohms) than 30 divided by the number of points under test, any place from which it is proposed to take current being considered as a point; the pressure used for testing should be twice that which it is proposed to use.

When all lamps and fittings are connected up, the insulation resistance between the conductors and earth is again tested, and this time must not be less in megohms than 25 divided by the number of lamps and other appliances. The insulation resistance between conductors must be equal to that obtained between the conductors and earth. The insulation resistance of any one branch circuit or any appliance must in no case fall below one megohm. Where power is taken from a public supply the tests of the completed installation will be made by the supply authorities before connecting to their mains.

CHAPTER III.—METERS.

METHODS OF CHARGING—WATT HOUR OR ENERGY METERS—MOTOR METERS—CLOCK METERS—ELECTROLYTIC METERS.

BEFORE we consider in detail the duties which an electricity supply meter has to fulfil, and the construction of the instruments that have been designed to fulfil these duties, it will be well to consider what it is that the engineer charges and the consumer pays for, and the conditions which affect the value of the supply to the consumer and to the engineer.

Now the electrical engineer is prohibited by the Board of Trade from charging his customers for anything but the work which he supplies, and consequently the instrument by which the consumption is to be measured should be an instrument for measuring work. The factors of power, as we have already seen in Section I., are current and pressure, and those of work are, therefore, current, pressure, and time, so in order to measure work we have to combine in one instrument three elements which shall measure these three quantities respectively.

Professor John Perry and others pointed out very many years ago that the simplest and most obvious way of attaining this object was by providing a motor which should require very little power to drive it, and whose speed could be made proportional to the power that was being supplied to the consumer. In this way, since the speed is proportional to the power, that is to the product of current and pressure, the number of revolutions per second is proportional to that product, and the total number of revolutions in any given time will be proportional to the product,

Current × pressure × time
or, Amperes × volts × hours,

which of course, represents work. Hence the instrument will become a "work measurer," if we merely add to it a revolution counter which will indicate for us at any time the total number of revolutions that have been made.

Though the work delivered by an electrical company to two different customers is the same so long as the total product of amperes × volts × hours is the same in each case, and the company would be, therefore, entitled to charge the same sum to each consumer; it does not at all follow that each consumer really gets the same value for his money if he buys the energy to light his house, because, though the amount which will be charged will be proportional to the supply pressure, yet the light which he will obtain from his lamps will be proportional to a higher power of the pressure than the first power. (*See* Fig. 618.)

In order to cope with this difficulty, the Board of Trade insists that a company supplying electrical energy for lighting purposes, must declare to its consumers the pressure at which the energy will be supplied, and not depart from that declared pressure by more than four per cent.

One result of this regulation has been to make it possible to employ meters for lighting circuits which do not measure energy at all, but merely the product of current and time, and are hence called ampere-hour meters, or coulomb meters, or sometimes quantity meters. The counter is graduated in ampere hours × the declared volts, and so reads Board of Trade units (*i.e.* 1,000 watt-hours). An ampere-hour meter on a circuit whose pressure is varying by two per cent. up or down, will clearly register at a rate varying only by two per cent., whereas, as has just been pointed out, the energy varies by double that range. It is thus not an absolutely correct instrument, although its use is sanctioned by the Board of Trade; and, indeed, it is sufficiently correct for all commercial purposes, since it tells in favour of the consumer and against the company if the pressure rises and the other way if the pressure drops.

METHODS OF CHARGING.

The way in which a consumer makes his demand upon the supply station is a consideration of some importance, as affecting the cost at which electrical energy may be produced. A little consideration will show that this must be the case, for the cost of production is made up of two main charges, capital charge and running costs, and a consumer who demands a small current for a comparatively long time in a day will evidently necessitate less capital expenditure on plant at the station than one who, taking the same total in the same time, demands a large current for a short time.

Until comparatively recent years the capital expended in purchasing the machinery, the buildings, and the electric cables, earned no money worth speaking of during the hours of daylight, because the demand for electrical energy was exclusively for the purposes of lighting, and the demand is still very much larger for lighting than for anything else. It is, however, now appreciated that if the lighting station can discover a sufficiently large demand in the day time to keep one or more machines fairly well loaded through the day, money may be earned by the same capital expenditure through a greater part of the twenty-four hours than was formerly the case.

The way in which the charges to different classes of demand are adjusted vary very much in different localities and under the direction of different engineers. Charges are, however, frequently adjusted by what is called a maximum demand indicator, which, as its name implies, indicates the maximum demand taken at any time. These principles were first brought into extensive application by Mr. Arthur Wright, who introduced his maximum demand indicator and the system of maximum demand indicating at Brighton, and the system is very commonly referred to as the Brighton system of charging.

A high ratio of maximum demand to average load does not, however, necessarily increase the cost of supply, unless the maximum is taken at the time of the greatest station load; and the indicator is lacking in information in this respect. The use of maximum demand indicators is often looked upon with disfavour by customers who do not understand them.

The maximum demand indicator of Mr. Wright consists essentially of a **U** tube containing a liquid upon the one end of which a closed, elongated, glass bulb is blown, and this is surrounded by a coil of strip copper carrying the main current. The glass bulb is filled with air, and this, when current passes round the coil, becomes heated, and expanding, depresses the liquid on that side of the **U** tube and causes it to rise on the other side and overflow into a graduated tube arranged to receive it; the amount contained in this graduated tube is therefore, apart from temperature errors, proportional to the maximum current used at any time.

Another instrument for the same purpose, the Atkinson-Schattner, is shown in Fig. 665. The coil shown has a series winding and attracts its plunger to a greater or lesser degree according to the current flowing. The plunger is attached to a pivoted quadrant which carries a scale graduated to read amperes. The quadrant carries a glass tube, bent as seen in the figure. This glass tube contains a number of steel balls, and is filled up with glycerine. The instrument is adjusted by the screw seen on the right hand side to read zero when no current flows, the balls all being in the upper part of the tube. When current is switched on the plunger tilts the quadrant through an angle corresponding with the current flowing, and some of the balls slowly fall into the lower arm, the number of balls down being a record of the "tilt," and so, of the maximum current used.

Another way of meeting the difficulty is that of charging each consumer a fixed annual amount per lamp connected, this amount corresponding with the capital expended on the machinery necessary to supply the lamp, and then charging him per meter for the energy supplied, the rate per meter being, of course, very much lower than in the ordinary flat rate charges, because it merely represents the second item referred to above, namely running costs.

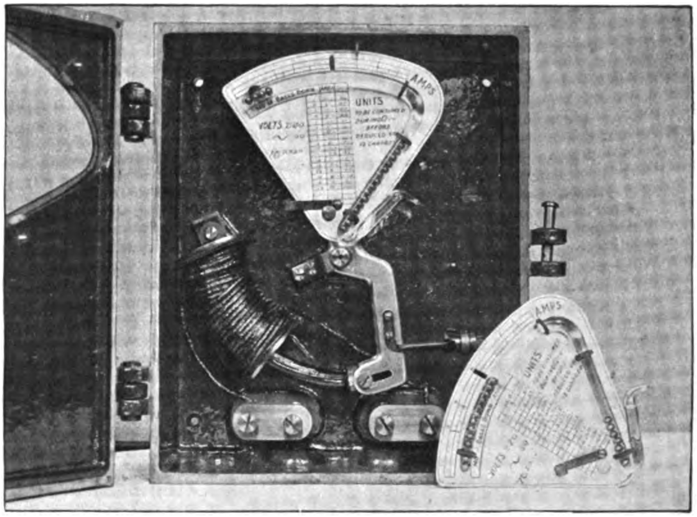


FIG. 665.—ATKINSON-SCHATTNER MAXIMUM DEMAND INDICATOR.

WATT HOUR OR ENERGY METERS.

It is quite clear that if an instrument is to measure the product of power and time, it must at least possess the function of measuring the power in some way; that is, it must have the essentials of a wattmeter (*see* Section V.).

Now, in all cases wattmeters contain a coil traversed by a current proportional to the pressure, which reacts with a coil traversed by a current proportional to the current to be measured. Generally the whole of the current to be measured passes through this latter coil. In the case of continuous currents the indication of the power is obtained by making one of these two coils movable. In the case of alternating current instruments, however, the two coils are frequently arranged so that they tend to produce a rotating magnetic field within whose sphere of action is placed a mass of iron or some other metal, which experiences a torque due to the rotating field. This mass of metal generally takes the form of a disc which is caused to rotate by the field.

MOTOR METERS.

The Elihu Thomson Meter is typical of all others. The principle is that of applying to a motor a turning couple or torque proportional to the power to be measured. The motor is relieved as far as possible of all frictional retardation, or any load other than one which shall be proportional to the speed. The result is that the speed of the motor is proportional to the power driving it. The production of a driving force proportional to the power to be measured, proceeds always upon one or other of the two lines which have been pointed out above. The production of a load or retarding force which shall be proportional to the speed, may be very simply accomplished by the generation of Foucault currents in a copper or other metallic disc rotated in a permanent magnet field. As a matter of practice, sufficient breaking action is usually obtained with three, or at the most four, permanent magnets of the horseshoe type acting on a disc between 2 in. and 4 in. in diameter. Now, it is essential that the braking action of this device shall be firstly proportional to the speed, and secondly, independent of temperature. With reference to the first condition, it is clear that, if we consider one magnet pole only and the two regions on either side as devoid of field, the E.M.F. generated in any little ring of metal in the disc we may care to consider—such, for example, as the imaginary paths of metal marked on the disc in Fig. 460—must be proportional to the rate of motion of the disc, provided the field produced by the magnet remains constant. The result of this E.M.F. is to set up a current, and the combination of this current in the metal with the field of the magnet, produces the retarding force which we desire. (*See* Section IV., page 234).

Now the path of the current, although complex, does not vary, the only two possible variants being the strength of the current and the strength of the field. The strength of the current in turn depends upon the E.M.F. driving it and the resistance of the path. As we have seen, the E.M.F. depends upon the speed of the disc, provided the field is constant, and the resistance of the path depends upon the temperature of the copper of the disc or of whatever other metal it may happen to be made. From this it follows, then, that provided the field of the magnet remains constant, the current at a given temperature is strictly proportional to the speed of the disc, and the retarding force therefore will be, as we wish it, proportional to that speed. Should the temperature of the copper change however, for example, if it rises, the resistance of the path will rise, and at the same speed as before the current will be less and the retarding force consequently less. The braking action therefore decreases with any rise in temperature. The variation of resistance of copper with temperature, however, is practically proportional to the temperature within ordinary ranges, and is not very large (0·4 per cent. per degree Centigrade).

Brake Magnets.—On the other hand any variation in the magnetic field reacts on the brake in two ways: firstly we may regard it as reducing the E.M.F. and therefore the current, and secondly the force due to that current is diminished, since it can only act in combination with a weaker field, thus two per cent. diminution in the field strength will result in a four per cent. decrease in the retarding force. It is quite possible to construct magnets whose strength is practically constant through all the ordinary ranges of temperature, and for a period of many years, the chief points requiring attention being the provision of a sufficiently large area for the air path and the proper ageing of the magnets.

The Thomson-Houston motor is mounted on the same spindle as that which carries the brake disc, and consists of an ordinary continuous-current motor wound without any iron in the magnetic circuit. The field is produced by two large fixed coils which carry the main current (Fig. 666). The armature has a high resistance, and is connected across the full voltage of the circuit whose power is to be measured. Owing to the absence of iron, the field produced by the main current coils is strictly proportional to the current flowing, and the armature is thus in a field proportional to that current. The armature itself carries a current proportional to the voltage, and hence exerts a torque proportional to the product of voltage and current. It is provided with a small silver commutator on which a pair of silver brushes press very lightly. If there were no variants and no other forces to be considered, the meter in this simple form would run at a speed strictly proportional to the power, and hence the total number of revolutions made by it in a given time would represent the integral of power and time during that period, and would hence give us a true measure of the energy delivered. In this simple form, however, the meter is liable to certain errors, the principal among these being those due to friction. The friction error, although quite negligible at the ordinary load, becomes of increasingly serious importance as the load diminishes, until it may well happen that the meter refuses to register the energy taken by, say, a single 16 candle-power lamp.

Friction is usually present in three distinct parts of the meter: firstly, in the pivots of the rotating armature; secondly, between the brushes and commutator when the motor possesses any device of the kind; and, thirdly, in the counting train. The first and last of these three sources of friction are always present (except in the Evershed meter), while the second has very commonly to be reckoned with. Mr. Evershed has pointed out that the magnitude of the friction moment in carefully designed motor meters, is commonly as much as one-fiftieth of the maximum driving moment, with the result that if the friction remains constant and the driving moment is strictly proportional to the load, there is an error at one-tenth full load of 16 per cent. in favour of the consumer. It will be seen at once how exceedingly important frictional errors become at low loads. To eliminate the friction of the various parts, extreme care is used in the manufacture and adjustment of all pivoted parts, and jewelled bearings are employed wherever commercially possible. Friction from the counting mechanism is generally reduced merely by making the various parts as light as possible and by fine pivoting. Various attempts have also been made to drive the counting mechanism electrically from the moving system without the interven-

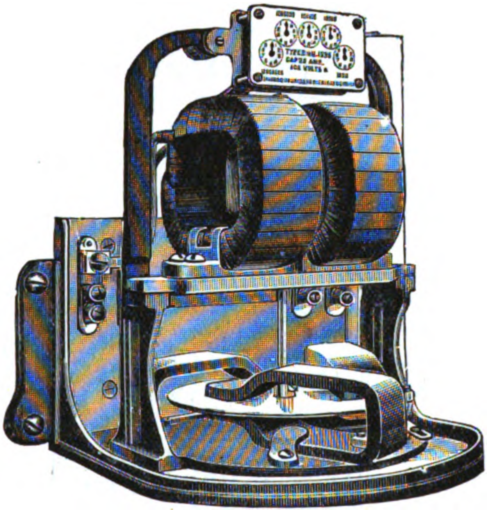


FIG. 666.—PROFESSOR ELIHU THOMSON'S ENERGY METER.

tion of mechanical gear, but without much success.

A supplementary coil is frequently used in series with the fine wire coil, but arranged to add to the magnetic effect of the series coil. This gives a small extra torque tending to overcome the friction effect. It must not be greater than the friction moment on any account, since that, of course, would cause the meter to register when no load was being taken. Unfortunately this device is not altogether satisfactory, for if it is to be of any use, this extra starting torque must very closely approximate to the friction torque when the meter is at rest. Now the friction torque will vary enormously if the meter is subject to vibrations from any cause. The consequence will be that if the extra starting torque is carefully adjusted in the test room when the meters are free from vibration, the meters will inevitably run if placed in the cellars of houses abutting on a main thoroughfare, or if mounted on the walls of buildings containing moving machinery or in the vicinity of such machinery. This particular behaviour of motor meters provided with the extra starting torque has given rise to very considerable trouble in practice, and is undoubtedly an objectionable feature.

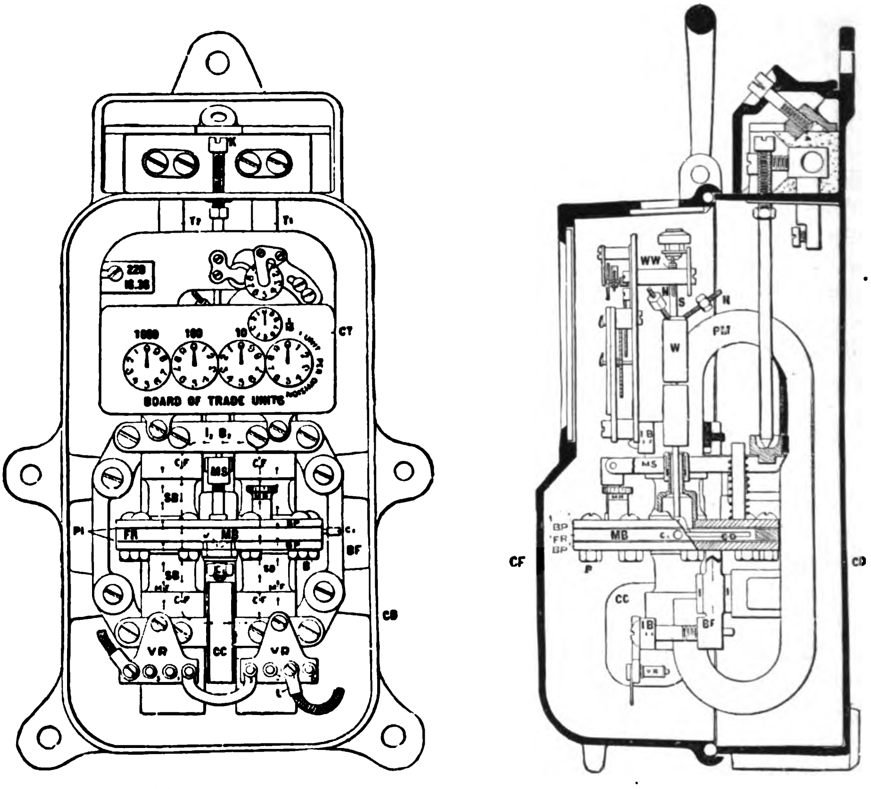


FIG. 667.—FERRANTI CONTINUOUS-CURRENT MOTOR METER.

One of the most ingenious, and presumably successful, devices of recent years employed to eliminate friction in supply meters is to be found in the pivoting arrangement of the Evershed motor meter, in which there is no top bearing but the armature is held in a vertical position by the attraction of an electromagnet placed above it, which also relieves the bottom pivot of most of the weight of the armature.

Ferranti Continuous-Current Meter.—The new type of continuous-current meter made by this firm is shown in Fig. 667. It is of the motor type, the driving torque being produced by causing current to flow radially through a copper disc immersed in mercury between the poles of a permanent magnet. The mercury bath M B is formed between two brass plates B P which are insulated from the mercury and separated by the fibre ring F R. The mercury tends to float the disc and so relieve the lower pivot, and it also serves as a nearly frictionless connection to the disc. The current enters the mercury bath at C_1 and flows through the platinum plated and enamelled copper disc C D to the contact C_2. The disc is unplated at the edge and centre in order to ensure that the current passes through it, and its buoyancy is adjusted by the weight W so that it just sinks upon the jewel J. The permanent magnet S D is that which acts upon the current driving the disc, while the magnet S B provides the braking effect; they are joined by the iron bars I_1 B_1 and I_2 B_2, upon the lower of which (I_1 B_1) a series compensating coil C C is wound, the purpose of which is to counteract the fluid friction due to the mercury, which increases with the load. Its action will be understood from the arrows shown in Fig. 667 of which M F show the normal magnetic field and C F show the direction of the compensating magnetomotive force. These arrows clearly show that the tendency of the compensating coil is to weaken the field of the braking magnet and strengthen that of the driving magnet. The mercury bath may be sealed for transit by means of the screw K, which depresses the mercury seal M S; and the bath may be filled up through the hole M H. Fig. 668 shows the top plate of the mercury bath with the pole pieces, mercury seals and bar I_2 B_2. By means of the variable resistance V R the constant of the meter, *i.e.* the number of ampere seconds per revolution, may be adjusted by shunting from 0 to 5 per cent. of the current. The meter is adapted for various voltages of supply by altering the index trainwork.

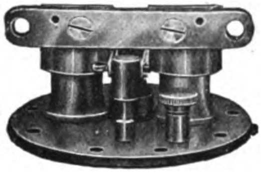


FIG 668.—TOP PLATE OF BATH IN FERRANTI METER.

The mechanism is bolted to a brass frame B F, which is carefully insulated from the cast-iron casing C B, and the terminals are conveniently placed upon the top of the casing.

The drop across the meter is in no case more than 0·1 volt, and in some meters is as low as 0·06, and as there is no shunt there can be no shunt losses. It is accurate within 1 per cent. from $\frac{1}{10}$ load to 50 per cent. overload.

The Ferranti Alternating-Current Meter shown in Fig. 669 is of the induction motor type and is a watt-hour meter. The principle upon which the meter depends is that of acting upon the eddy currents produced by a very inductive shunt, with a field produced by a series winding.

The aluminium disc in which the eddy currents are induced is seen at D. The shunt coil ShC surrounds the core C of a special tubular electromagnet T M, the core has two outward radial poles, P^2, and the shell has three inward radial poles P^1, the poles being arranged alternately as shown. The core and shell are shown separately in Fig. 670. The series system consists of a slotted armature S A (*see* Fig. 671), arranged so that its slots come almost immediately over the poles P^1 and P^2, and wound with a series coil SeC, the winding being of a wave form. The braking effect is produced by a permanent magnet P M.

Since the shunt coil is so largely surrounded with iron it will have great self-induction, and no additional apparatus is necessary to produce this desired effect. The eddy currents produced by the shunt field will therefore be in phase with the impressed E.M.F., and the series field acting upon them in phase with the load current; the driving torque will therefore be proportional to the product of these two and to the cosine of the angle of lag, *i.e.* the true watts flowing. The meter may be given a slight constant torque to compensate for friction by moving the series coils through a small angle in the plane of rotation by means of screws s^1 and s^2, and the constant of the meter may

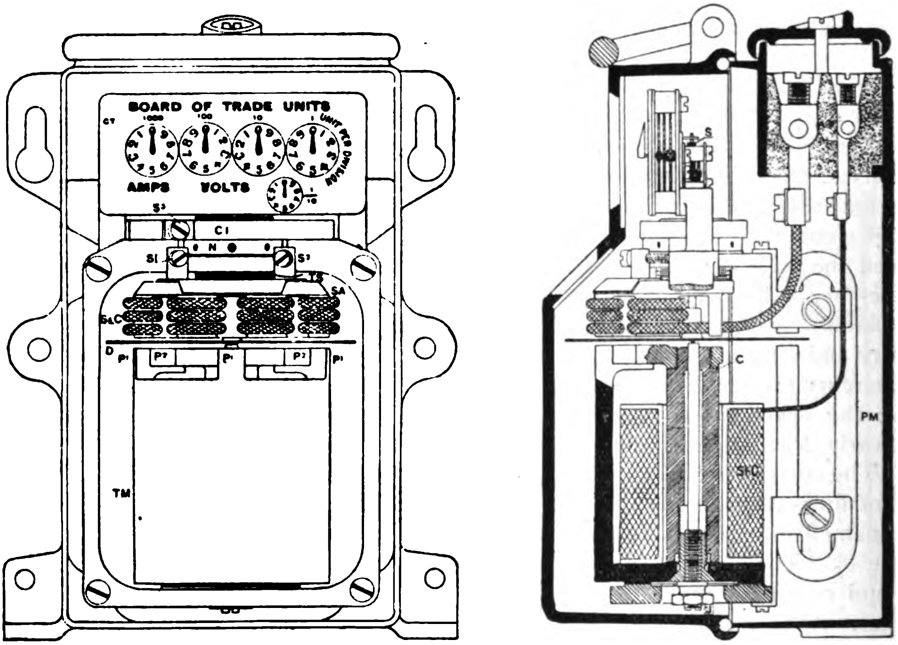


FIG. 669.—FERRANTI INDUCTION SUPPLY METER.

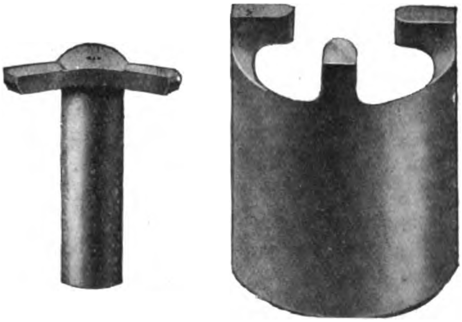


FIG. 670.—IRON PORTIONS OF SHUNT FIELD SYSTEM.

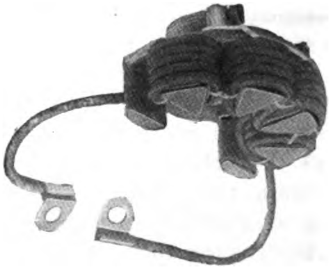


FIG. 671.—SERIES COILS AND POLES.

be altered by adjusting the nut N which lowers or raises the series armature. The instrument is simple, compact, and strong, and its accuracy is not affected by changes of power factor or wave form.

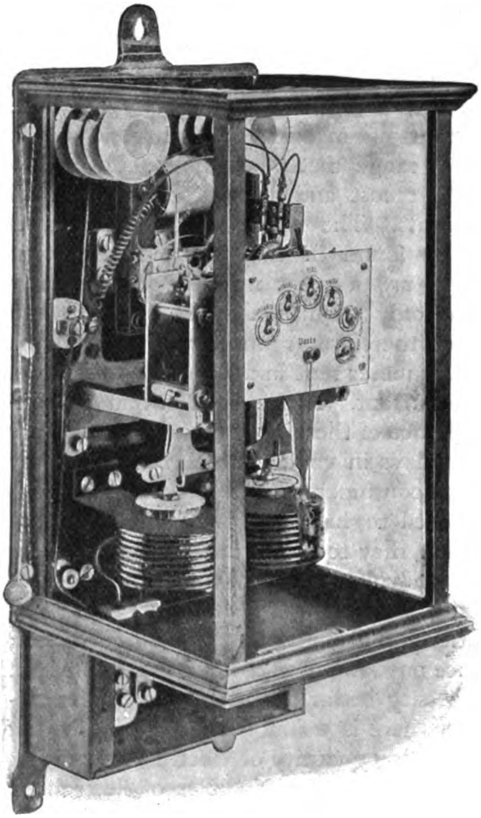


FIG. 672.—THE ARON ENERGY METER.

CLOCK METERS.

Aron.—This meter depends upon the change in rate of swinging of a pendulum which occurs when a change is made in the effective force due to gravity. The change is made by superposing a magnetic pull upon that due to gravity. The action is as follows:

Through the two large stationary coils seen in the lower part of Fig. 672 the current to be metered is passed, and above each of these is suspended a pendulum whose bob consists of a coil of fine wire. These two pendulums control two clock trains which drive the recording train through a differential gear; the recording train therefore records the difference of the rates of the two clocks.

The fine wire coils of the pendulums are connected across the full voltage of the supply in such a way that there is a force of attraction between one bob and its coil and repulsion between the other and coil. The fine wire coils and the series coils contain no iron, and the difference in the rates of swing is proportional to the watts.

To obviate any error from want of synchronism (apart from magnetic control) the current through the pendulum coils is automatically reversed every ten minutes; the error is thus alternately in favour of and against the consumer, and so cancels

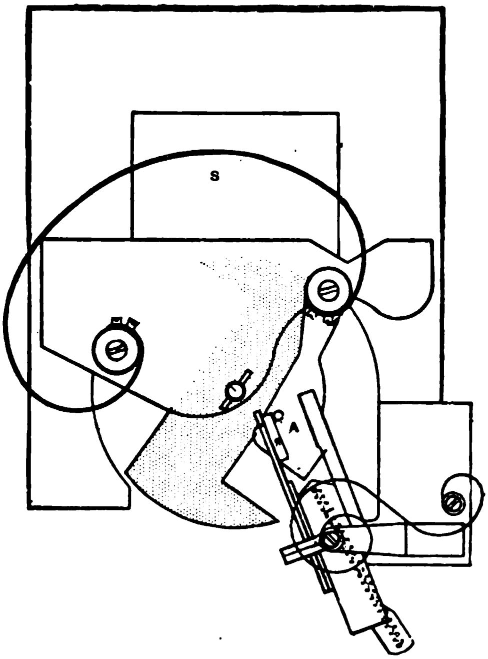


FIG. 673.—DIAGRAM OF WINDING GEAR IN NORMAL POSITION.

out. The recording train is reversed at the same time in order that it may still read in the same direction.

The electrical winding gear is shown in Figs. 673 and 674. It consists merely of an electromagnet (the exciting coil of which is not shown in Fig. 673, but may be seen at C in Fig. 672), provided with a pivoted, laminated, **Z**-shaped armature, which is allowed to rotate through an angle of 75 degrees.

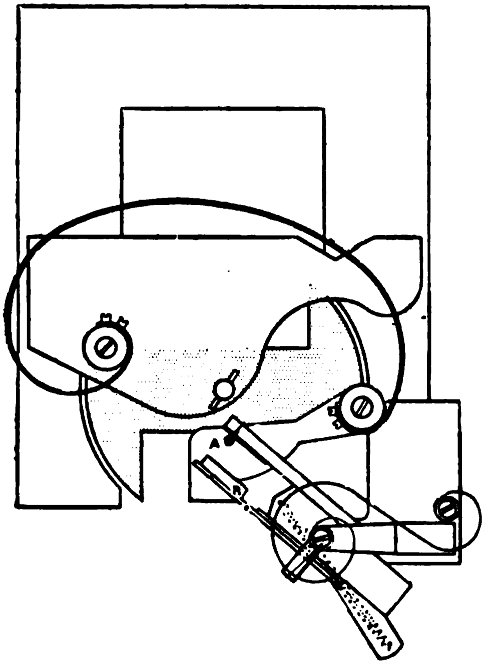


FIG. 674.—DIAGRAM OF WINDING GEAR; SPRING FULLY WOUND.

When the spring S is unwound (Fig. 673), current passes through the pin A to the switch R and excites the magnet; the armature then swings round to its position in Fig. 674, winding the spring and moving the switch to the off position.

Mordey-Fricker.—Among recently developed clock meters may be mentioned the Mordey-Fricker meter, which for simplicity can hardly be equalled. It consists essentially of an inexpensive clock, having its ordinary mechanical balance replaced by an electrically controlled one, by which the rate of running of the clock is made proportional to the current flowing.

ELECTROLYTIC METERS.

One of the great difficulties which meter makers have had to contend with is that of meeting the demand for a small range meter which should be low in first cost and accurate for very small currents. The origin of the demand is to be found in two facts: firstly, that there are a great number of consumers who only require a small current, and who, therefore, cannot afford to pay a heavy meter rent in addition to the cost of the current. And, secondly, that in consequence of the higher pressures which are nowadays in vogue, the current taken by small consumers of the order referred to is reduced to half or less than half of that which they took at pressures of the order of 100 volts. It is obvious at first sight that the meter which shall fulfil these conditions can only be an ampere-hour meter, since any form of watt-hour meter must of necessity be far too expensive. Theoretically there is no more accurate method of measuring quantity of electricity than that which applies the principles of electrolysis, but it is hard to obtain in practice a meter with the necessary qualities. The meter must be simple in its mode of registration and in the interpretation of the record; it must not cause an undue waste of energy; and, finally, it must not require frequent attention on the part of the central station officials.

Registration.—It is open to us to electrolyse either a solution containing a metallic salt, when the deposit formed will be of the metal contained in the solution, or a liquid which will be broken up into one or more gaseous constituents. The registration obviously must record the total amount of metal or of gas liberated. In the case of the metal, the weight of the metal is the only index of the amount which can be employed, except in the case of mercury, where the volume may with greater ease be employed as a gauge of the weight. In the case of a gas, one must either measure the volume of the gas or the loss of volume of the liquid electrolysed.

If a solution of a metallic salt be employed a fairly heavy current may be passed through the electrolyte, but it has been found that any automatic method of measuring the gain in weight of the cathode is hardly practicable. In the exceptional case of mercury, on the other hand, the automatic registration of the amount of metal liberated has been very easily and simply effected, by allowing it to collect in a graduated tube, from which the volume is read off. In the case of liquids giving off gaseous constituents two methods have been adopted, one being the measurement of the gas liberated, and the other that of the loss of volume of the remaining liquid. All the devices depending upon the former method, however, have failed to reach much more than an experimental stage, and do not come within the scope of this work. The latter method, on the other hand, has met with commercial success, and is to be found in one of the meters in use at the present day. Its application has, however, been restricted to customers with small demands.

Waste of Energy.—This is, perhaps, the most serious difficulty with electrolytic meters, owing to the very considerable loss of pressure occasioned in such instruments by the high resistance of electrolytes in general, and by the inevitable back E.M.F. of polarisation. The most obvious method of dealing with the former of the two troubles is by shunting the meter, reliance being placed on the maintenance of a constant ratio of resistance between the cell and its shunt. On the other hand, the presence of any back E.M.F. of polarisation tends to vitiate the value of such a shunt, since the back E.M.F. is to all intents and purposes constant, while the drop down the shunt and that due to the resistance of the cell, are, of course, proportional to the current. To meet these difficulties attempts have been made to eliminate any back E.M.F. of polarisation by employing two electrodes of the same metal as that of the salt in solution, or to add to the cell circuit a compensating forward E.M.F. to neutralise its effect. A shunt has, however, in almost all cases been resorted to, the Bastian meter being about the only meter with any commercial success which is unshunted. In any unshunted meter, particularly one which relies upon the breaking up of a liquid into gases, there will be an inconveniently large polarisation E.M.F., and in the Bastian meter this amounts to as much as two volts. To the consumer this, of course, matters little, since the meter only tells ampere-hours against him, and he has to provide himself with lamps to run at two volts less than that of the supply ; but to the station engineer the loss of two volts, or one per cent. (at the higher pressure) of the current he sells is a serious matter.

A further correction which has to be applied to meters of the shunted electrolytic type, is a compensation for the change in resistance of the cell and of the shunt with temperature. Fortunately, however, this is not difficult to carry out, since the resistance of the cell falls with a rise in temperature, and, of course, the resistance of an ordinary metallic conductor rises. It is usually sufficient, therefore, to connect a copper resistance in series with the cell, giving it such a value that its rise in resistance over the whole range of temperature change will be just equal to the diminution of the resistance of the cell for the same temperature change.

The resistance of the cell will not only vary with temperature, but also with the distance between the electrodes and with the concentration of the electrolyte. The arrangement adopted by Mr. Wright to avoid this source of error will be best understood when a general description of the meter has been given.

Wright Meter.—The meter consists of a glass tube entirely sealed, and having its upper end blown out into a rather curiously shaped head (Fig. 675). This head is so formed as to be capable of retaining mercury in an annular channel surrounding the top cylindrical portion of the tube. On one side of the head there is a form of bulbous annex D, which communicates with the annular channel A, and serves as a reservoir for mercury; the annular ring of mercury forms the anode of the cell. The cylindrical portion of the tube contains the carbon cathode B, and below this a **U** tube, provided with a funnel-shaped opening at its upper end, is placed.

The whole of the tube and its head is filled with a solution of a double iodide of mercury and potassium, with the exception of the volume occupied by the mercury and of a small bubble of air. The funnel-shaped opening of the **U** tube is attached to the sides of the tube, and mercury collects by electrolysis on the cathode, falling from it into the funnel. It then collects, as indicated, in the lower portion of the **U** tube, until it reaches the top of the left hand bend, when it automatically syphons over and discharges into the lower portion of the main tube. The cathode being placed beneath the anode, facility is offered for the concentrated liquid which is formed in the neighbourhood of the brimful anode to fall towards the cathode, and a slight but sufficient circulation of the electrolyte is maintained along the stream lines indicated in Fig. 676. This shows the latest form of tube head used by the firm, G being a glass rod fence and C the cathode, now made of iridium. It is to this circulation device more, perhaps, than to any other portion of the invention, that the meter owes its success. Further, the maintenance of a constant level in the anode channel ensures a practically constant

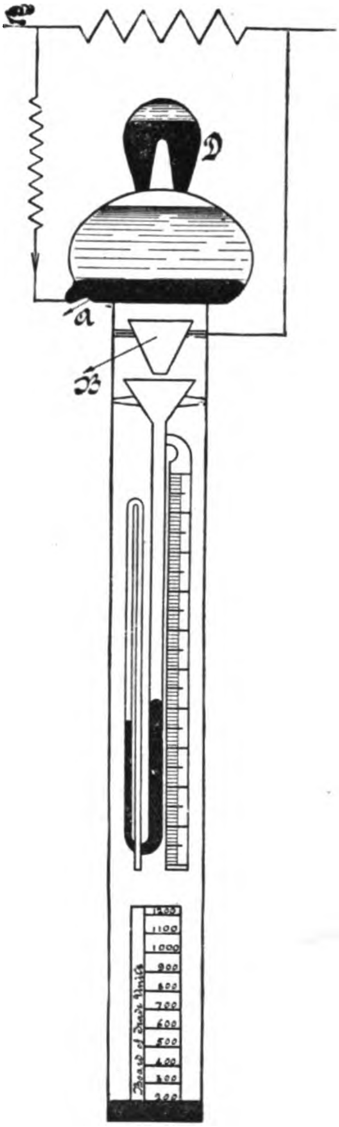


FIG. 675.—WRIGHT ELECTROLYTIC METER.

resistance of the cell, since the length of fall from anode to cathode is practically invariable. When the whole of the mercury has thus passed to the bottom portion of the main tube, it is easily replaced by the simple operation of tilting the meter upside down, when the dense mercury naturally returns mostly to the reservoir, leaving, however, a small surplus to be collected in the anode channel. It will be seen that every one of the usual errors has been guarded against in this meter. The lower portion of the tube acts like a second hand to an ordinary dial, while the syphon tube gives the first hand reading, *i.e.* small quantities. The drop in volts down the complete shunted meter does not exceed one volt at full load, the shunt resistance to the five-ampere size being ·2 of an ohm, and the resistance of the cell and its series wire amounting to about 37 ohms.

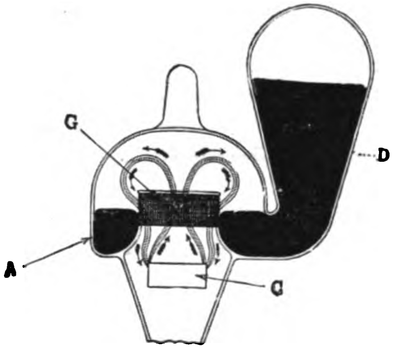


FIG. 676.—STREAM LINES IN WRIGHT METER.

The Bastian Meter.—This meter consists of a simple glass jar containing slightly acidulated water, and registration is effected by the fall of level of the top of the liquid as the volume is decreased by electrolysis; the error due to evaporation is checked by floating a film of oil on the surface. The electrodes consist of two platinum plates placed at the bottom of the jar, leading-in wires being carried in glass tubes to the top of the jar. Since the acid is in no way affected by the electrolysis, it follows that replenishment only calls for the addition of water. The total drop in volts due to resistance and polarisation E.M.F. is about 2½ at full load when the meter is full, but as the electrolyte is broken up and increases in density the fall decreases.

The prime objection to such a meter is the waste of power, but apart from that, if engineers are content to sacrifice a small amount of power to ensure greater accuracy, and if the electrolyte is not subject to serious diminution by bubbling, and also by adhesion of drops to the sides of the glass tube as the level falls, nothing whatever can be said except in praise of the accuracy of the meter, for it will record even a small leakage current.

PREPAYMENT METERS.

These are now used extensively and are very useful for small consumers. The prepayment mechanism must comprise a switch of some sort which either operates or is allowed to be operated by hand upon the insertion of the coin, and which automatically cuts off the current when the power paid for has been consumed.

The problem of their manufacture really consists in producing a meter sufficiently cheap to justify the supply company in buying it for small consumers and yet sufficiently accurate to meet the Board of Trade requirements.

SECTION IX.

SWITCHGEAR.

CHAPTER I.—SWITCHES AND SWITCHBOARDS.

SWITCH DESIGN—SWITCH CONSTRUCTION—TYPICAL SWITCHES—SWITCHBOARDS—TYPES OF SWITCHBOARD—EXAMPLES OF SWITCHBOARDS.

THE various switches used in electrical engineering may conveniently be classified under the following three headings, accord-to their functions, viz. for controlling, directing, and measuring. The first two functions are not uncommonly combined in one and the same switch, though in the case of very large currents or high potentials it is frequently necessary to separate them, while switches of the third class are for use in conjunction with measuring instruments. This last class consists of specialised highly insulated keys and plugs, whose general type has been described in Section V. They are used chiefly on alternating current boards. The first class, viz. controlling switches, may further be classified as (*a*) hand operated; (*b*) electrically operated; while those under class (*b*) may be further differentiated as either hand controlled or automatic.

SWITCH DESIGN.

The essential requirements which a switch must meet are, firstly, absence of danger to operator; secondly, avoidance of injury to property; and, thirdly, mechanical soundness and general reliability. The first of these requirements has principally to contend with risk of shock from dangerous voltages, and therefore can only be fulfilled by very thoroughly insulating all live parts which might otherwise be exposed to contact with the person of the operator.

Even in low voltage work danger of injury may arise from the moving handle of an automatic switch; or, again, from burning.

Danger to Property.—Danger to property arises from possible heating, and from a sudden rise of potential. Heating may originate in any of the three following ways: The current may be too heavy for the metal portions intended to carry it; the switch resistance too high owing to improper design or workmanship, or through wear, or current may pass through parts not designed to carry it, such as springs, screws, etc.; or a defective insulator. The remedy is to be found in the provision of adequate insulation and the rigid avoidance of current in metal parts not really intended to carry it. In the case of extra high-tension switches, the provision of adequate insulation is not perhaps very simple, but for voltages up to 6,000 much difficulty is not to be apprehended. A further cause of heating is far more serious than any yet mentioned. When a circuit carrying current is broken, the self-induction invariably causes a flash across the gap, and the vaporised metal produced by this flash fills the gap; in these circumstances quite a low pressure which is unable to jump $\frac{1}{16}$ in. in air can maintain an arc between the metal surfaces several inches apart. The arc thus drawn out between the separated portions of a switch is of a most destructive character. If allowed to continue, it will not only melt large masses of metal, but in high-tension circuits will leap from one part to another of the switchboard. It is impossible entirely to prevent the formation of the arc, and the attention of the switch designer must be directed to confining it between surfaces which either are not damaged by it, or are but slightly damaged at each operation, and made capable of renewal. In many cases it is also open to him to arrange matters so that the arc formed has a very short life, with the result that the metal parts have not time to become vaporised and the supply current is unable to follow the self-induction flash. In the case of direct-current circuits, the rapid extinction of an arc is very liable to occasion a serious inductive rise of potential, capable of breaking down the insulation of the circuit; so that for direct-current work the practice of providing renewable arcing surfaces is followed. With alternating-current circuits, however, a long drawn out arc is fraught with great danger to the whole system of mains, from possible resonance effects, and since these are cumulative, a rapid suppression of the arc is highly desirable. We find in consequence, particularly on high-tension circuits of which the long, heavily insulated cables have a high capacity, that switches are used in which the break occurs under oil, with the result that the arc is suppressed with great rapidity.

SWITCH CONSTRUCTION.

The materials employed for the conducting portions of switches are copper and brass, cast copper being scrupulously avoided and only the best drawn copper employed. For those portions which have to be made springy, hard rolled copper is best, although hard, springy brass, may be equally well employed for small currents where there is sufficient space available to give the increased dimensions demanded. In many cases renewable carbon contacts are provided for those portions across which arcing occurs.

Dimensions.—The two most important dimensions in a switch are the area of contact surface and length of break; the former needs to be proportioned with reference to the current to be carried, while the latter depends further upon the voltage employed. The contact surfaces across which current has to be carried continuously should invariably be arranged so that on making or breaking they are subjected to a rubbing action, which keeps them clean. In switches of large capacity, difficulty arises in providing really intimate contact between sufficiently large areas; this is met by subdividing one of the two and forming it of the ends of springy metal laminæ, the other surface being continuous.

In switches of small capacity, and where laminated contacts are not employed, a current density on the apparent area of contact of 100 amperes per sq. in. may be allowed, while in surfaces between one solid and one laminated conductor the normal density should not exceed 250 amperes per sq. in. and the maximum 400 amperes. When new, it will be found that these values occasion a drop of 25 millivolts at the contact, the resistance of the contacts being from 0·000007 to 0·0001 ohms per sq. in., depending upon the materials and pressure at the contacts.* The contact surfaces must all be most carefully finished and fitted. The final operation is to grind them in with very fine emery and oil, the movement of opening and closing the switch repeatedly supplying the grinding action. It is impossible practically to obtain actual contact over very large surfaces, and it is remarkable in this connection how efficacious is a film of oil on the contact surface in removing heating trouble. The action of the oil, in all probability, is that of a conductor, owing to the extreme thinness and large area of the film: or it may serve as a medium in which fine particles of copper or brass are suspended, forming conducting threads.

---

* Hellmund, Vienna. *Z. f. E.*

Insulation.—The insulation of low-tension switch parts is invariably provided by slate, marble, porcelain, or ebonite, while for high-tension work marble, porcelain, mica preparation, or special materials such as ambroin, etc., are used. In low-tension work, slate meets with the greatest favour in this country, chiefly on account of its mechanical strength, cheapness and good appearance when enamelled. It is open to the great objection that metallic veins are frequently hidden in it, and these sometimes are the cause of much trouble through leakage, and occasionally even may cause a dead short circuit. Where trouble of this kind arises, the holes in the slate through which conducting parts have to pass, may be bushed with ebonite or other insulator. Slate is commonly employed for bases up to 500 volts, but above this pressure some better material, such as marble, is advisable. Ebonite has the great disadvantage of being combustible, and therefore finds an application limited to small parts, and to covering operating handles, and similar uses. For low and medium voltage work switch handles may be made of wood fixed on to live metal.

Arc Extinction.—The length of break to be used should be not less than that shown in the following table for ordinary switches with the break in air.

MINIMUM TOTAL LENGTH OF BREAK IN AIR IN INCHES.

CURRENT STRENGTH IN AMPERES.	300 VOLTS, ALTERNATING OR CONTINUOUS.	1,000 VOLTS, CONTINUOUS.	UP TO 2,000 VOLTS, ALTERNATING.
5	⅞	4	4
50	1⅝	8	10
200	4	13¼	15¼
500	7¼	16 7/16	20

In addition to a long break the following are the chief methods that are employed to interrupt the arc:—

(1.) Rapid separation of the contacts beyond sparking distance, no time being allowed for the metal to vaporise.

(2.) The final interruption of the circuit between contacts of some "non-arcing" metal, such as zinc, the vapour of which has a low conductivity.

(3.) The arc is blown out either by a blast of air or magnetically.

(4.) The contacts are separated under oil, which prevents them from heating sufficiently to vaporise any metal; the weight of the oil also suppresses the arc.

(5.) The arc is cut in two by the insertion between the contacts of a slab of some non-inflammable insulating material.

(6.) The circuit is broken at a number of different places at once; the arc thus distributed generates insufficient heat at any point to vaporise an appreciable quantity of metal.

TYPICAL SWITCHES.

A few typical constructions of switches are illustrated on page 737. Fig. 680 is a small switch for light duties, such as lighting circuits, and is not usually designed in sizes above 20 amperes. The pivoting of the handle is about the same axis as that of the U-shaped laminated bridge, so that these two move about the same

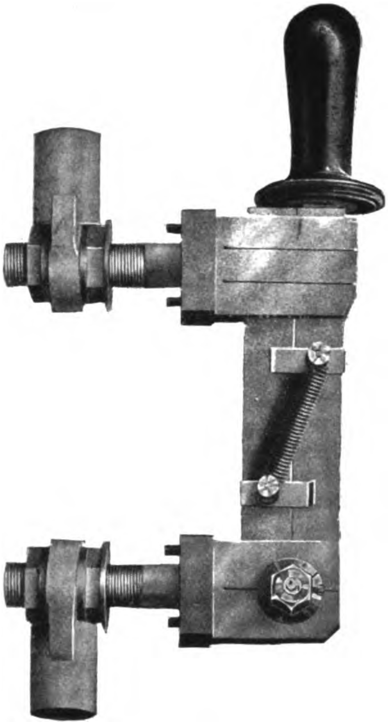


FIG. 677.

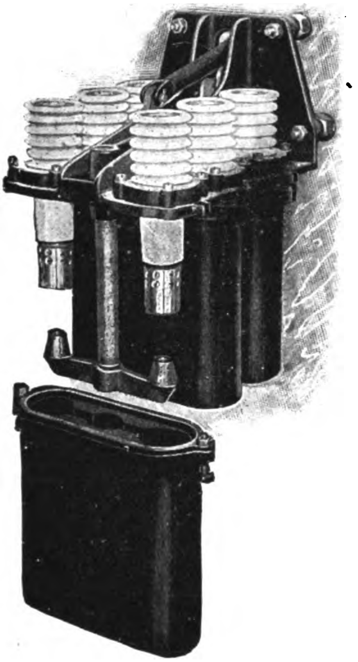


FIG. 678.

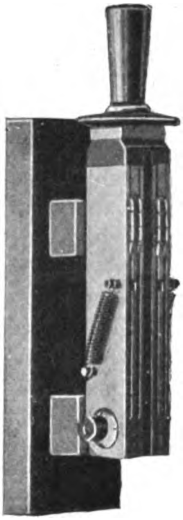


FIG. 679.

2,000 AMPERE KNIFE SWITCH.

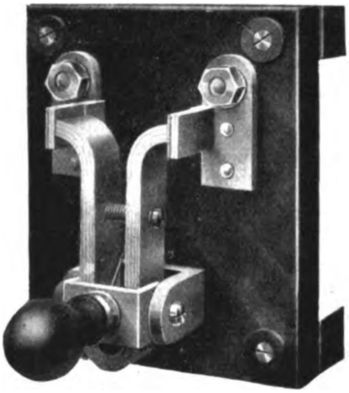


FIG. 680.

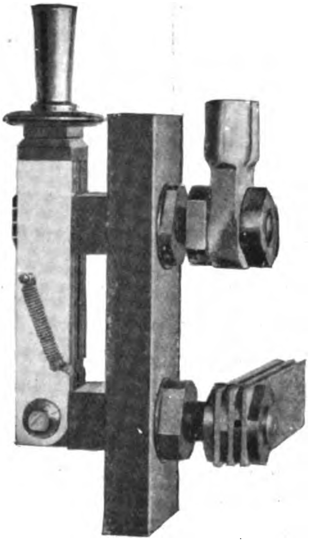


FIG. 681.

BACK VIEW OF FIG. 679.

FIGS. 677 TO 681.—TYPES OF SWITCHES IN MODERN USE.

axis but independently of one another. When the switch is closed, a light spring is kept in tension, giving a force insufficient to open the switch; when it has been opened by depressing the handle, the spring causes a rapid break. The base of the switch is of enamelled slate, and contact with the terminals is made from behind by sockets and bolts.

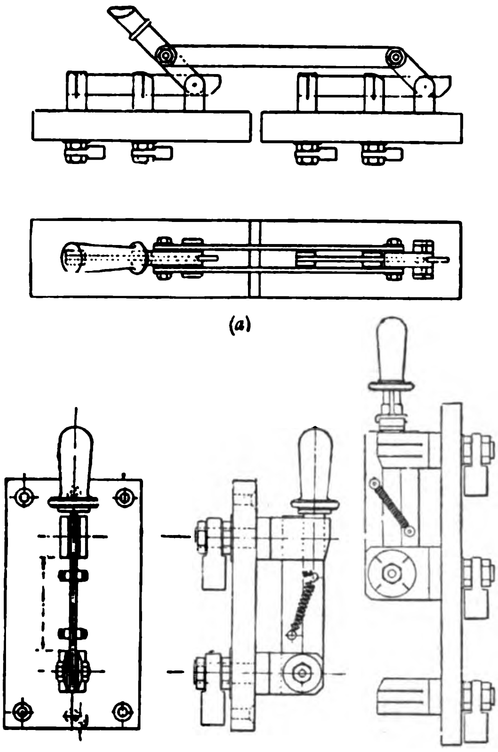


FIG. 682.—TYPICAL SWITCH CONSTRUCTIONS.

Fig. 677 is a type of switch of very old general design which has come latterly into very general and extended use. It is known as a "knife switch." The blade or knife is made in two portions, for the purpose of obtaining a quick break. The hinging together of the two portions is effected by a somewhat ingenious construction, shown in Fig. 683 on this page. An annular recess is provided, half in one blade and half in the other, and into this recess a steel washer is snugly fitted. The heel of each blade is cut away so that in opening the switch the outer blade can move through a given angle before the other is forced to follow; the latter is brought quickly away by the springs. The fixed contacts are mounted on blocks provided with steady pins, and with long bolts for the reception of the cable sockets.

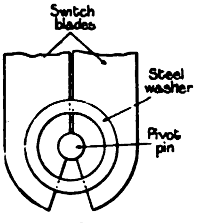


FIG. 683.—HEEL OF KNIFE SWITCH.

To avoid passing current through a pivoted portion, a second contact similar to the upper one is sometimes provided. Such a construction is illustrated in Fig. 682*a*, where a tandem knife switch is shown. The tandem construction is simply for the purpose of giving a double pole break.

For currents above 500 amperes, the blades are usually made in one piece giving slow break, and several blades are mounted in parallel on one base. A double-pole change-over switch, with quick break in both positions, is shown in Fig. 682.

High-tension.—A typical high-tension three-phase oil switch made by the Westinghouse Company is illustrated in Fig. 678. A separate oil tank is provided for each phase. The movable contact consists of a horizontal copper bar, having a coned plunger at each end and supported at the middle by a wooden rod. The coned plungers when the bridge is raised enter hollow coned contacts of springy copper, held in position by porcelain insulators. The three wooden rods are secured to an iron bar at the top of the switch, and the raising of this bar by suitable links and levers closes the three phases simultaneously. The oil tanks are of iron, lined with teak thoroughly impregnated with the oil, the lining serving to prevent arcing to the sides of the tank, to minimise the amount of oil required, and to reduce the dimensions of the path for the arc.

SWITCHBOARDS.

In cases where the number of switches needed is considerable, they are concentrated as far as possible into one place, and mounted on one structure called a switchboard. The switchboard thus becomes a kind of nerve centre from which the circuits radiate. This concentration is desirable from several points of view. It enables the difficulties or breakdowns which may arise to be dealt with far more readily and promptly ; it greatly facilitates testing and repairs ; and, further, conduces to less expensive insulation than if the switches were scattered. A switchboard should therefore be so designed as to emphasise the above advantages as far as possible, and should possess the following qualities in an eminent degree viz. : (*a*) simplicity, (*b*) independence of parts, (*c*) ease of repair, (*d*) smallness of dimensions. A complicated switchboard is far more liable than is a simple one to break down through some fault of its own, and also to be the indirect cause of a breakdown in an emergency by causing confusion in the mind of the switchboard attendant. Independence of parts can only be obtained in a limited sense, since practically all parts are interconnected. At the same time, provision should be made for isolating various parts, and, where possible, by automatic means. Such provision greatly adds to the ease of repair, which should be further studied by careful grouping of the circuits. The actual portion of the switchboard carrying parts to be handled or observed should be kept as small as reasonably practicable in order to bring as much of it as possible under the control of one man, and so ensure connected operation of all parts. This has resulted in the development of "remote control" gear, in which bulky switches are placed remote from the main switchboard and controlled by small handles and push buttons on the board itself.

Reliability of action can only be secured by the most systematic subdivision of the apparatus and, where there is any question of reliability of action, by duplicating such parts. Subdivision should be carried out in strict sequence from each generating unit to the outgoing feeders ; it is only by this systematic procedure that really reliable switchgear for large powers has been successfully developed of recent years.

The most imminent risk of breakdown is from fire, and in view of this, all inflammable materials should be rigidly excluded. The mounting of switches, busbars, etc., on slate, marble or porcelain, for low, medium, and high pressures respectively, at once ensures noninflammability of these parts ; but since it is necessary to connect on to outgoing feeders from the switchboard, and to provide numerous other cable connections, the introduction of a dangerous element is very difficult to avoid. For low voltages the connections in question may be insulated sufficiently with asbestos, or by being stretched bare between porcelain insulators; but for higher pressures, asbestos is absolutely useless as an insulator, and bare conductors can only be tolerated when placed high up or otherwise quite beyond the reach of an operator.

TYPES OF SWITCHBOARD.

There are three main types of switchboard in use at the present day, viz. the flat back, which is the oldest of all, and still meets with acceptance for low-voltage work ; the front cellular, introduced by Mr. Ferranti, and suitable for medium and high tensions ; and, thirdly, the cellular construction, in which the cells or compartments are much larger and

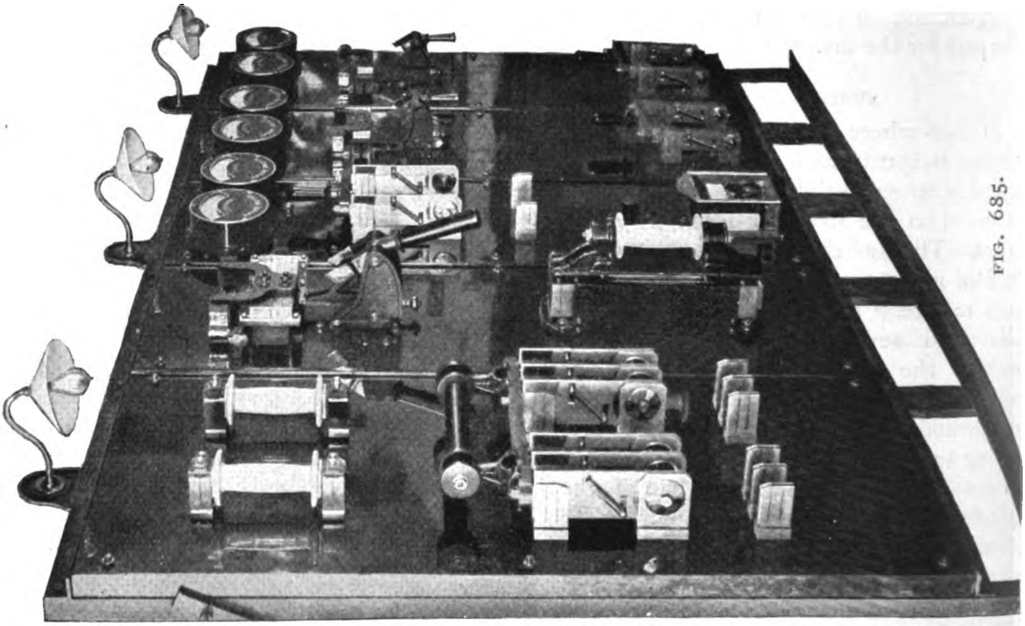


FIG. 685.

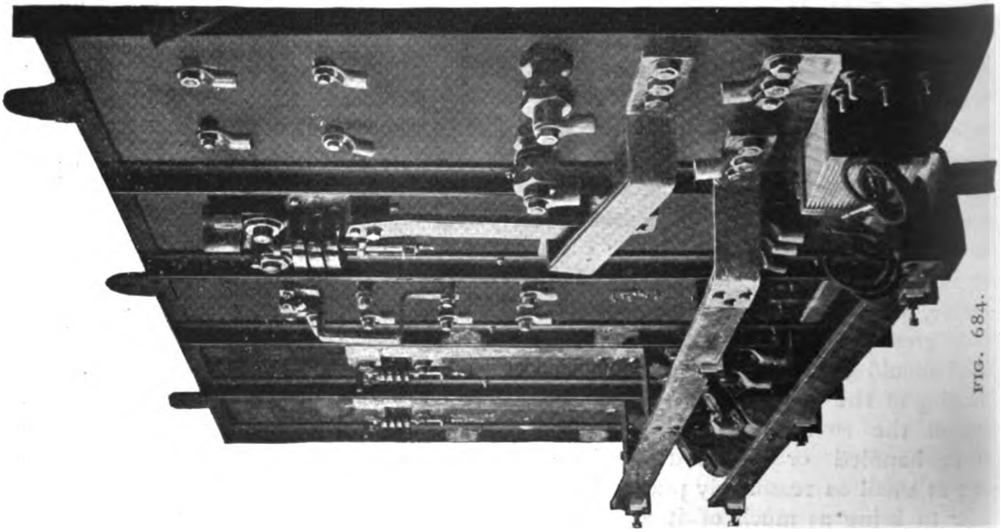


FIG. 684.

more elaborate than the original Ferranti board, and are placed either behind the controlling panels or beneath them. This type has been largely developed both in this country and abroad, and finds its especial application in high-tension work, while a slightly modified form of it is employed for extra high tension work up to 60,000 volts.

CONTINUOUS-CURRENT SWITCHBOARD.

Figs. 684 and 685 show the back and front respectively of a flat-back switchboard for continuous current at 500 volts. The board is divided into panels, of which the left-hand one constitutes the main generator panel. This carries a double-pole double-throw quick-break knife switch for 2,000 amperes. Above it are two porcelain-handled fuses; to the right of this on the adjacent panel is a circuit breaker, controlling a feeder; below this again is a porcelain handled fuse, and an integrating wattmeter to the right on the next panel. The rear view shows the massive busbars of bare copper strip, and an ammeter shunt for 2,000 amperes at the bottom to the right, the various cable sockets and circuit-breaker coils being also clearly distinguishable.

GLASGOW BOARD.

Figs. 686 and 687 show the practice followed at the Glasgow tramway generating station. The safety of operation of this board is obtained by placing all high-tension parts high out of reach of persons standing on the ground. The high-tension bars are bare and painted red; they are 10 feet or more from the ground, as seen in Fig. 686. The switches are of the air-break, carbon-tip type, and the three phases, operating at 6,500 volts between the phases, are separated from one another by white marble partitions. These can be seen at the top of the board in Fig. 686, and also the handle projecting through the panel below each switch and to the right of it. Connection between switch and handle is provided by rods and levers. All the measuring instruments are of the low-

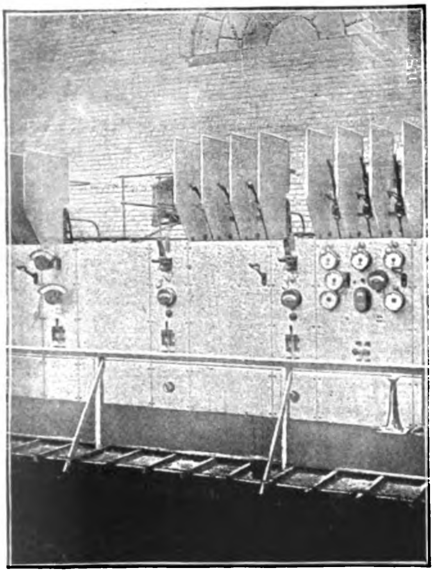


FIG. 686.—WESTINGHOUSE BOARD AT GLASGOW.

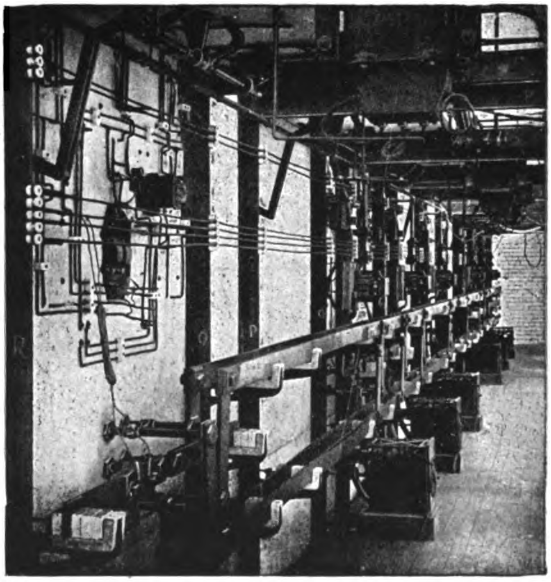
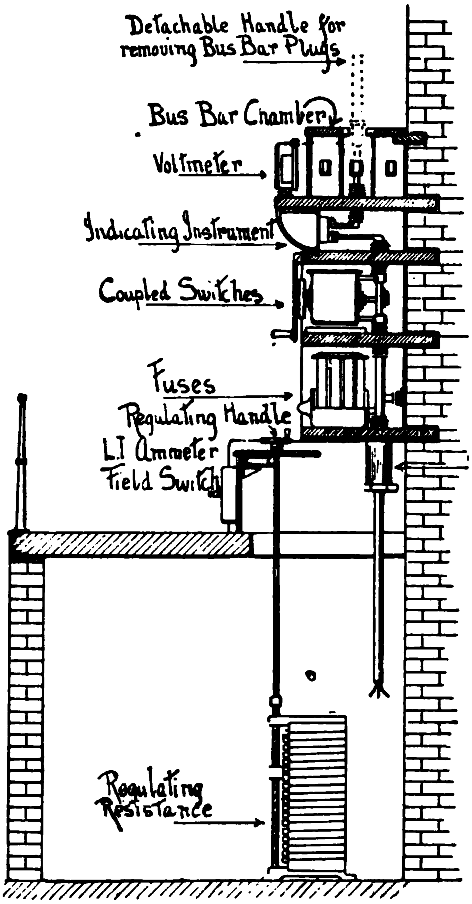


FIG. 687.—EXCITATION BUSBARS ON GLASGOW BOARD.

voltage type operating through instrument transformers. The transformers are placed with the high-tension parts 10 feet from the ground and the low-tension circuits feeding the instruments are seen in Fig. 687, together with the 100-volt exciter of busbars and connections.

FERRANTI BOARD.

Fig. 688 is a typical Ferranti board, the pioneer of all " no-back " boards. The chief characteristic is that each possible break in the circuit is enclosed in a fireproof insulating cell. Thus each phase of every switch has a cell to itself, as has also each fuse, each instrument and each busbar. The cells are constructed by grouting thick slate, or other insulating slabs, into the wall to form horizontal shelves, as can be seen in Figs. 688 and 689. These shelves are also provided with grooves into which vertical partitions of the same material slide, so producing the cells. The path of the current is from the busbars, down through the slate to the ammeter cell, out of this into the switch cell, then into the fuse cell and finally to the cable end. The passage from one cell to another through the slate slab is always protected by porcelain, and the contacts at the back of the fuse cell are supported by porcelain insulators. These details are best shown in Fig. 689 where, too, the earthenware tank carrying the oil break fuse is seen. These, as well as contacts, are provided in duplicate. The busbars are accommodated at the top, each in a cell by itself. Each panel can be isolated by removing a plug, an insulated detachable handle being provided for the purpose to be inserted through the top of the busbar cell. Voltmeters and synchronising gear are mounted on a level with the busbars. The ammeters can be removed bodily as seen in Fig. 689, where the ammeter contacts only



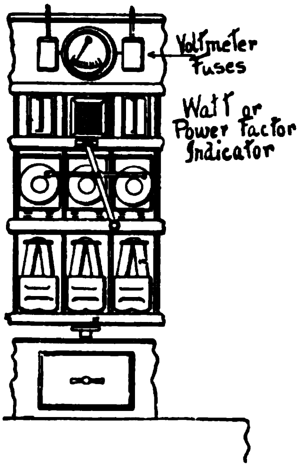


FIG. 688.—SECTION OF FERRANTI CELLULAR TYPE BOARD.

are shown in the cell above the switch. All operations of isolating, unplugging, switching, replacing fuses, etc., can be carried out with perfect safety even while the board is live, and accidental contact with live metal is impossible. Further, there are no straggling cables, and the space occupied by the board is remarkably small. The illustrations also show the field-regulating gear, viz. switch, ammeter and rheostat, with its handle, arranged at the bottom of the board in a convenient position.

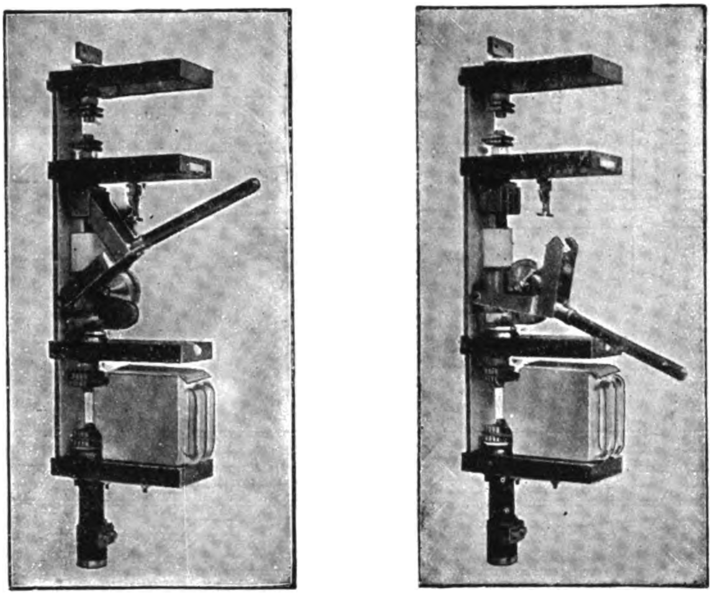


FIG. 689.—FERRANTI CELLULAR SYSTEM.

The high-tension switches are locked in the "off" position by panels slipped into the front of the cells and holding the switch handles down. The backs of the cells are lined with insulating fireproof slabs as shown in Figs. 688 and 689. The "coupled switches" of Fig. 688 are those in the three phases of one circuit.

CARVILLE MAIN BOARD.

In Fig. 690 is illustrated a switchboard which embodies and emphasises the prime requirements of modern high-tension work. It was designed by Mr. C. H. Merz and Mr. William MacLellan for the Carville station at Newcastle. Front, back and sectional views are given both of a generator and of a feeder panel. The construction is of the Ferranti or cellular type, although there are two sides to the board, so that it has a back. All the switches are electrically operated. The busbars (three phase) are provided in duplicate, and the parts are arranged in galleries one above the other. The whole structure is rather a switch building than a board, since it is 37 feet high. The index letters on the illustration sufficiently explain the functions of the various parts; the operating desk, from which all is controlled is placed some distance away. The voltages controlled are 5,500 and over.

The exciting circuits in an alternating-current station must be given very careful attention, since failure of the exciting current is almost as serious as failure of the

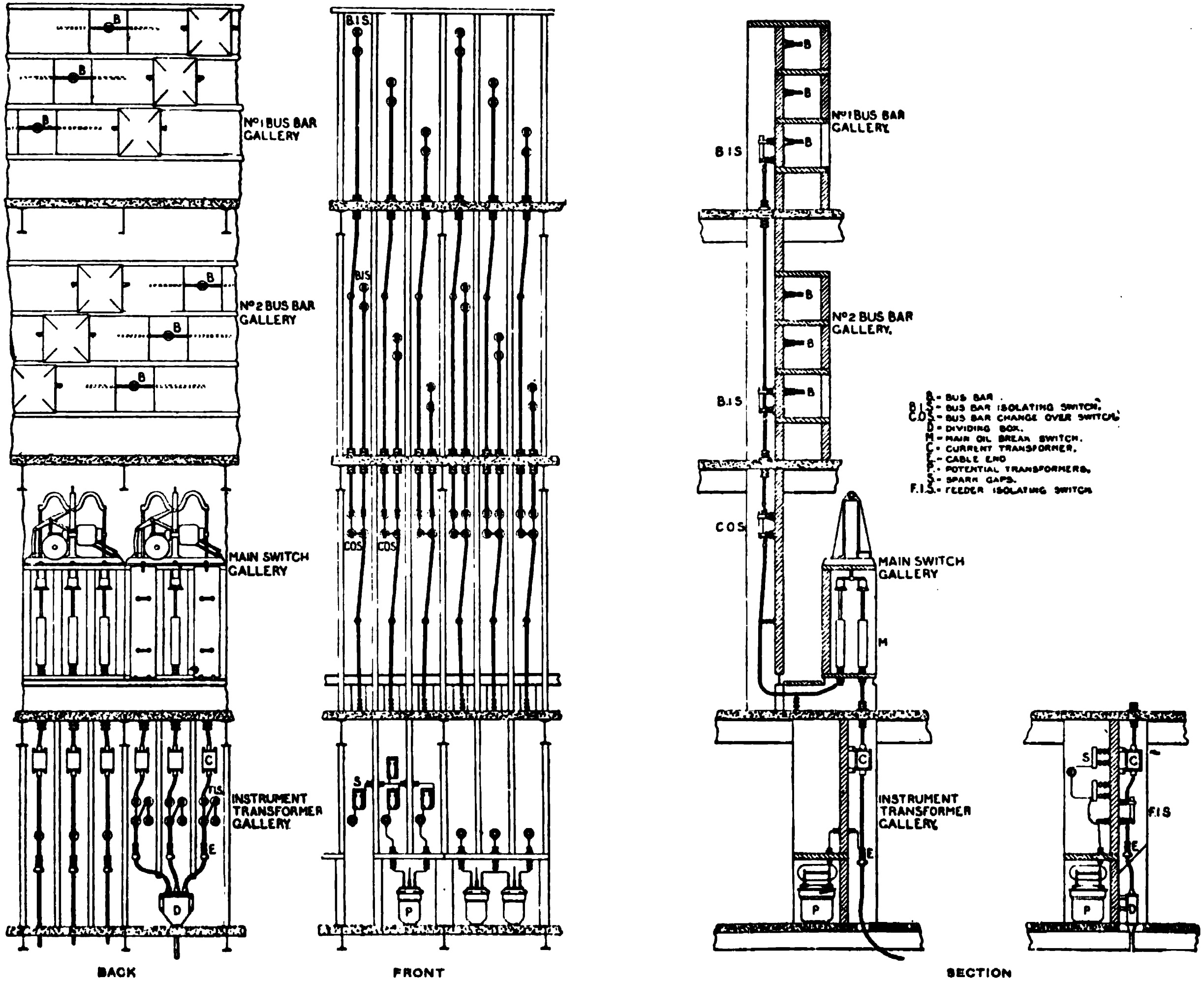


FIG. 690. HIGH VOLTAGE MAIN SWITCHBOARD AT CARVILLE, NEWCASTLE.

main circuit. The practice was common at one time of providing each alternator with its own self-exciting shunt-wound exciter, which was direct coupled to the alternator shaft. The arrangement is excellent from the point of view of simplicity but suffers from want of flexibility and from the fact that any fall in speed of the prime mover affects the generator voltage doubly. For small, comparatively high speed, units the method is fairly satisfactory, especially if the fly-wheel effect is large, but where the number of units exceeds two or three it is preferable to employ two or more independent exciters and excite the alternators from special exciting busbars. A battery may be usefully added as a standby and also to give light in the event of a complete shut down, while the modern use of electrically operated switches makes the addition of a battery imperative. For so varied and heavy a responsibility, however, it should be duplicated.

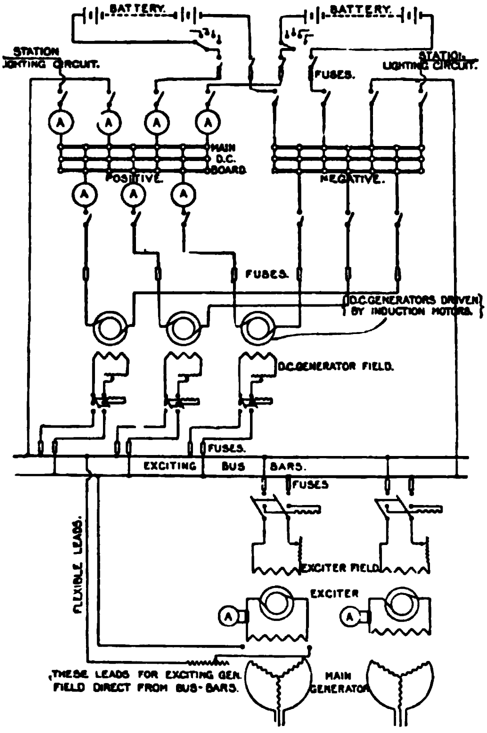


FIG. 691.—EXCITING CIRCUITS AT CARVILLE, NEWCASTLE.

An extremely flexible and very perfect arrangement is in use at the Carville station; a diagram of the circuits is given in Fig. 691.

The exciters though direct-coupled are not self-exciting, but are excited in turn from direct-current exciting busbars. The exciting busbars are fed from one or more of three motor-driven generators through a main direct-current plugboard by which any one of these generators may be plugged on to (1) the left-hand battery; (2) the right-hand battery; (3) the station lights; (4) exciting busbars. The circuits may be easily traced in Fig. 691.

FERRANTI EXTRA HIGH TENSION.

A typical example of extra high tension switchgear is shown in Figs. 692 and 693. The example shown represents the practice followed for a generator panel, a feeder panel, and a "summation" panel, the latter giving the total output where several units are in use, or several feeders are supplied from one unit. In Fig. 692 is shown what may be called the back view, and in Fig. 693 the front view. The board consists of three vertical cubicles set side by side to one another, and back to back to another set of three. The cubicles are subdivided into cells, each of which is perfectly fireproof, after the original standard Ferranti pattern. Referring now to Fig. 692, the left hand is the generator panel, both doors of which stand open. In the top compartment are the three isolating switches, one for each phase, an insulating handle for operating these being shown at the foot of the summation panel door. Below the isolating switches is the remote control oil switch, and below this again is an ammeter trans-

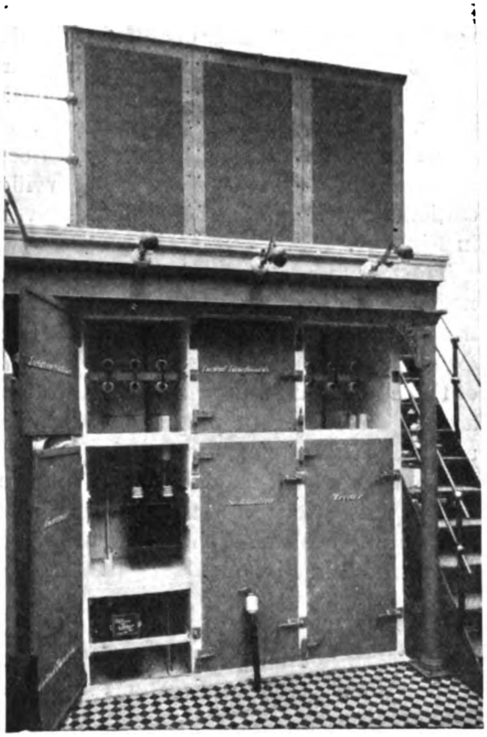


FIG. 692.—FERRANTI EXTRA HIGH TENSION SWITCHBOARD.

former. The function of the isolating switches is to isolate this particular panel from the busbars for cleaning, repairs, etc. In the generator panel on the other side, as shown by the open door in Fig. 693, is the generator potential transformer in the centre, with its fuses below and the busbar compartments above. The summation panels merely contain current and potential transformers, and the feeder panels are identical with the generator panels, except that no potential transformer is required. The function of the potential transformer is to supply a voltmeter, of course, and only one is therefore needed. The back of the control desk, above the panels, is seen in Fig. 692. The conducting metal within the cubicles is all bare, porcelain and oil being the only insulation, there is no crossing of leads, and the busbars are accommodated in cells at the top of the panels. By these means the reliability of the gear is ensured in the highest degree possible, since all inflammable covering to the conductors is eliminated and the remote position of the busbars from subsidiary apparatus and circuits reduces the risk of their being involved in any trouble arising in the latter.

Fig. 694 is a diagram showing the circuits of three sections of the switchboard on the alternate-current side at Fairclough Lane sub-station, Liverpool. The induction motor shown forms the alternating-current side of a 225 kilowatt motor-generator, the direct-current side of which supplies low tension current for distribution locally.

This station is tapped on to a feeder running from the main generating station to places beyond, and in order that trouble in such places may not shut this one down an overload cut-out is inserted in the outgoing feeder. Reverse power action is used in both sets of feeders to prevent any station feeding back to a breakdown with energy taken from its battery by its direct-current

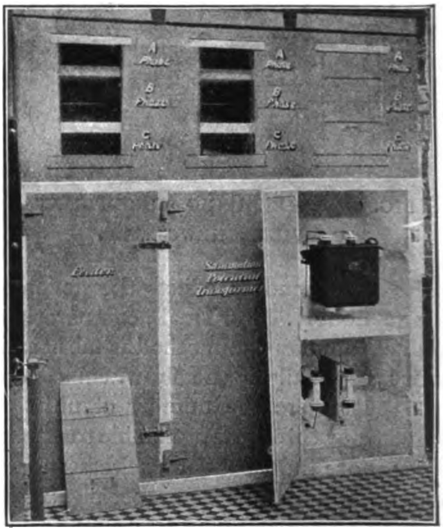


FIG. 693.—FRONT VIEW OF FIG. 692.

generator. The battery serves to operate the tripping coils of the oil switches, and it will be noted that the overload relays are all connected to *three* phases through a series transformer in each phase.

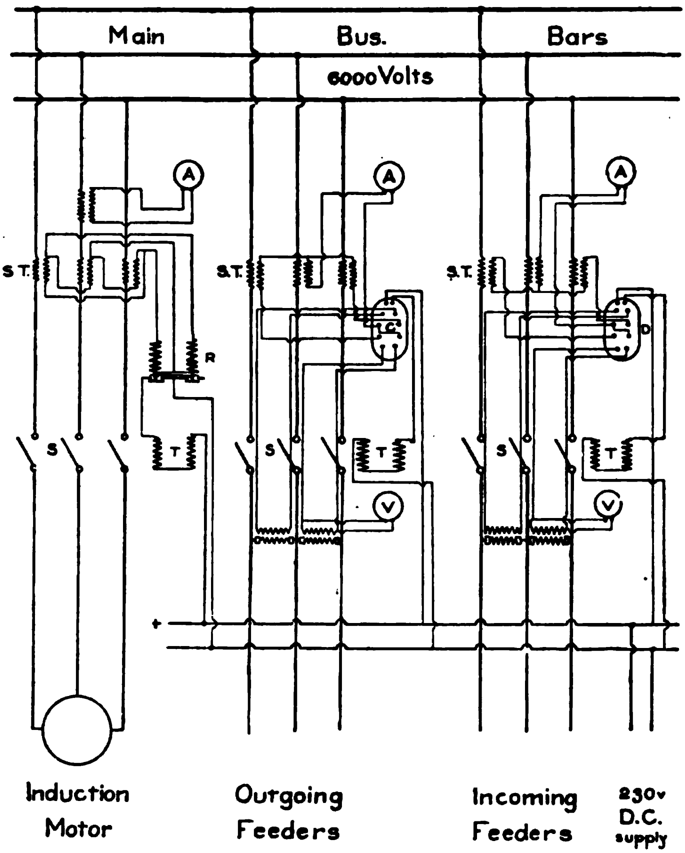


FIG. 694.—SWITCHING CIRCUITS AT FAIRCLOUGH LANE SUB-STATION, LIVERPOOL.

A = Ammeter; V = Voltmeter; R = Time limit overload relay; T = Tripping coil on oil switch; C = Polyphase overload and reverse current relay; D = Polyphase reverse current relay; S = Automatic oil circuit breakers; S.T. = Series transformers.

WESTINGHOUSE MINE BOARD.

Fig. 695 (page 748) shows a three-phase high-tension board for colliery underground work erected by the Westinghouse Company. The cubicle system of construction is followed, busbars running along an enclosed compartment at the top, from which connection is provided to each feeder panel below. Projecting from the front of the board at the top are the handles of the isolating switches, below these an ammeter and its lamp, and below these again the overload circuit breaker. The isolating switches may be padlocked in either the off or on position. The wiring inside a cubicle is shown in Fig. 695, where the isolating switch is seen at the top, to the left of this are highly insulated series transformers for the ammeter and tripping coils of the circuit breaker, and in the centre the oil circuit breaker with its tank. The potential

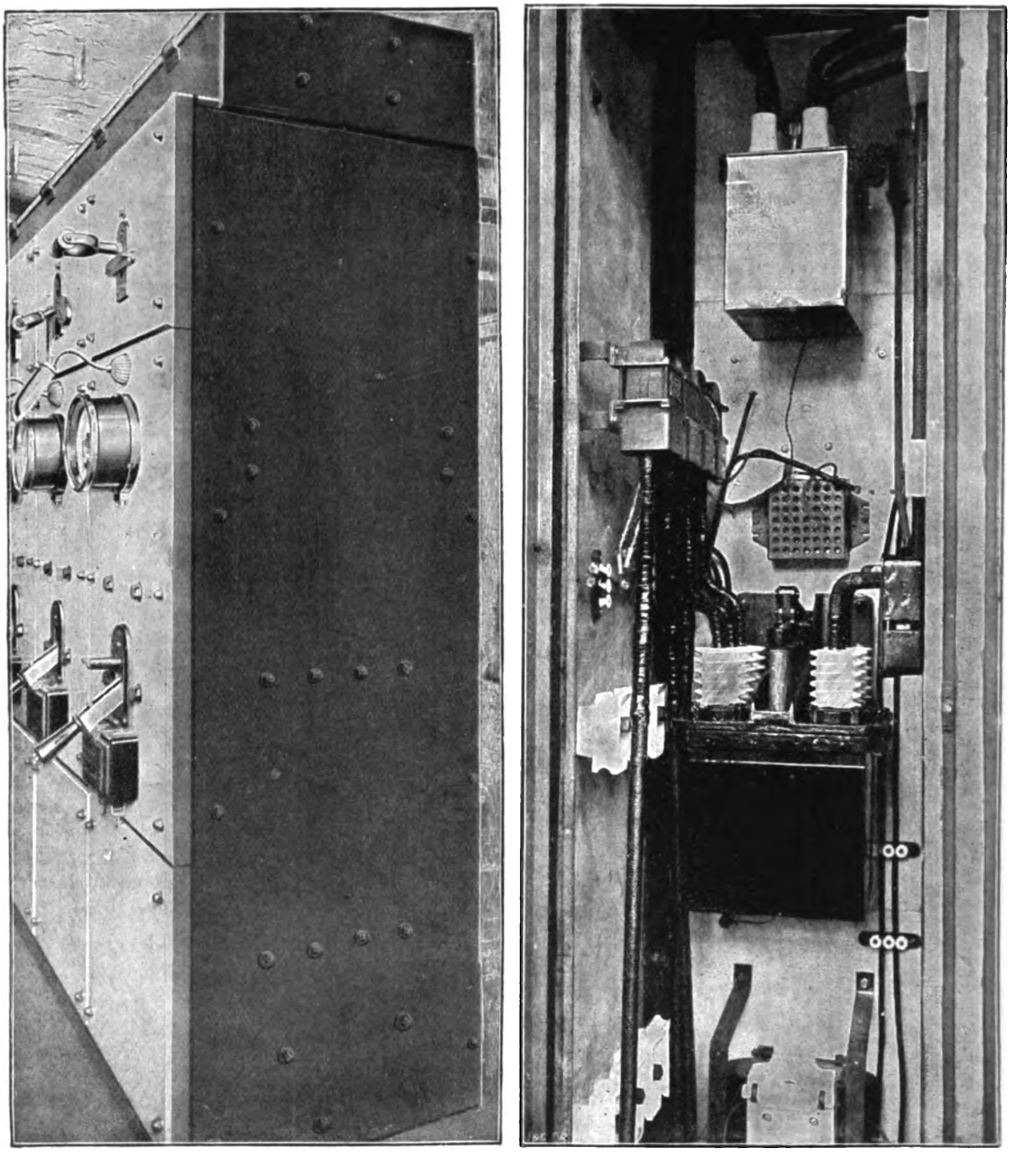


FIG. 695.—FRONT AND REAR VIEWS OF WESTINGHOUSE HIGH TENSION COLLIERY SWITCHBOARD.

transformer with its fuses is at the bottom. It will readily be understood that in colliery switchboards, it is of the utmost importance, not only to restrict all arcing or sparking to closely confined spaces, such as those within oil tanks, but also to eliminate risk of shock to the utmost degree possible.

CHAPTER II.—BOOSTERS, BALANCERS AND SPECIAL SWITCHGEAR.

BOOSTERS — BALANCERS — REVERSIBLE BOOSTERS — CIRCUIT BREAKERS — ALTERNATING CURRENT RELAYS—CIRCUIT-BREAKING OIL SWITCHES—SYNCHRONISERS—LIGHTNING ARRESTERS.

A VERY interesting class of machine has come, of late years, into increasing prominence. Its function is to supplement the output of the main generators in a special manner, and automatically, with a view to obtaining both better regulation of the distributing system and better operation of the main generating units. The supplementary aid is afforded (1) by adding voltage to the current distributed ; (2) by adding current to the mains at the required voltage. The first method involves sending the current through machines in series with the main generators, and the second, putting machines in parallel with the main generators. The former constitute the larger class and are called *boosters*, while the latter are called *balancers*, their application being limited to balancing three-wire or multi-wire networks. We will consider the former class first.

BOOSTERS.

The simplest boosters are series-wound machines capable of carrying a heavy current and of generating but a few volts. They are driven by a motor and placed in series with one or more feeders, and are designed to work on the straight line portion of their characteristics. They thus add a voltage proportional to the current, and so automatically compensate for the drop in the feeders to which they are connected, since the drop is also proportional to current. The compensation may be exact or slightly in excess. In tramway work they are often used in the negative, or return, feeders of the overhead system, in which case the fields are excited by the positive feeder current and the armatures are in series with the negative feeders. Three such machines driven by a shunt motor are shown in Fig. 696, the largest machine of the four being the motor.

Of equal, if not greater, importance is the application of boosters to battery work. By their aid, charging current can be taken from, say, lighting busbars at 230 volts, and driven into accumulators which normally discharge on the same busbars, but which for a complete charge need 300 to 320 volts; the booster supplies the added 70 to 90 volts, and is shunt wound or separately excited for such duty.

In a battery whose voltage is controlled by cutting cells at one end in or out, the end cells have a short life and give much trouble. Modern practice is to use a reversible booster which shall boost a charge into the cells when needed, shall

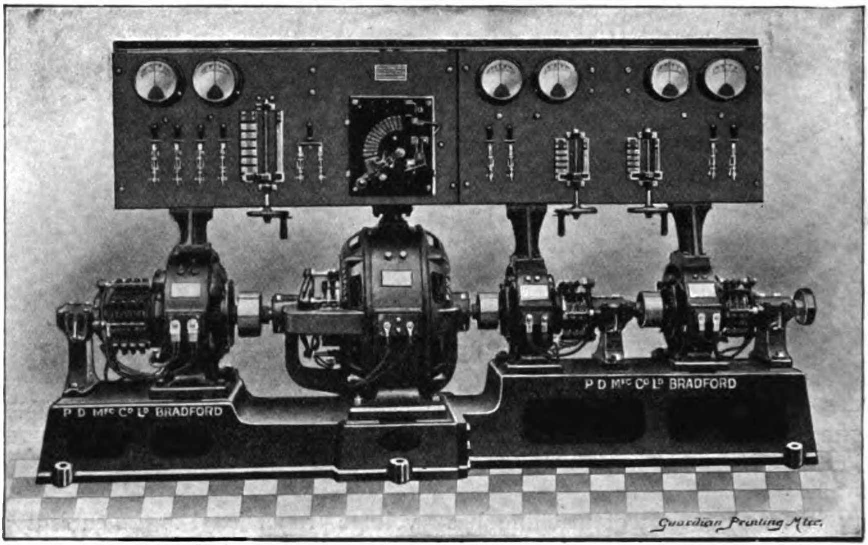


FIG. 696.—SHUNT MOTOR DRIVING FEEDER BOOSTERS.

oppose an E.M.F. to that of the battery on discharge when the battery voltage is too high, and shall add an assisting voltage to the discharge when the battery is low. Hand regulation of these functions is impossible on rapidly varying loads, and automatic operation is arranged for. By this means a battery may be made to supplement the main generators in a most economical manner, the generators (and their prime movers) being kept loaded at their best efficiency, and the battery providing the excess at periods of high load and taking a charge at low-load times, so keeping the generators busy and efficient even then.

BALANCERS.

The ordinary balancer consists of two identical machines on one bed-plate and direct coupled. The armature and field circuits are crossed, as shown in Fig. 697. When the voltages on both sides are the same the machines run idly in their bearings. If, say, the voltage on the positive side drops owing to heavy load, the field of the negative armature is weakened and that of the positive strengthened (*see* Section X.). The former therefore "motors" more and takes power from the more lightly loaded (negative) side, while the latter generates under the increased speed and excitation and assists the more heavily loaded (positive) side.

REVERSIBLE BOOSTERS.

The Highfield Booster. — Prominent among booster systems is the Highfield Booster (Figs. 698 and 699). The amount of "boost," or added volts, is determined by the difference between the battery volts and the E.M.F. of a small constant voltage machine called the exciter. The booster field is connected between the exciter and

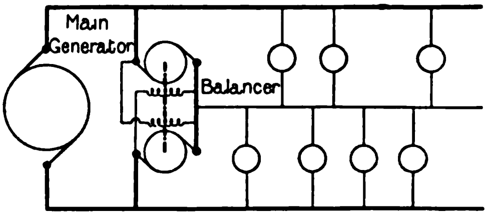


FIG. 697.—THREE-WIRE BALANCER CIRCUITS.

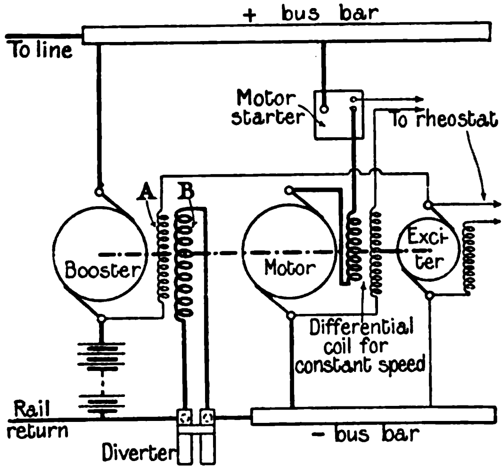


FIG. 698.—CIRCUITS OF HIGHFIELD BOOSTER.

A = Booster field coil; B = Coil to correct armature reaction.

battery, so that when the battery overcomes the exciter, current goes through the field one way, and when the exciter voltage is the higher the current is reversed. The booster field coils and armature are so designed that the latter generates a voltage exactly equal to the voltage across its field coils. Exciter, booster and motor armatures are all mounted on one shaft (Fig. 699), and the motor is compounded for constant speed. On discharge the exciter becomes a motor, since it carries current against its armature E.M.F. No regulating cells or switches are needed for the battery, since the booster armature automatically provides a regulating voltage whichever way it is required. The field magnets are laminated to allow of rapid variations and reversal of flux. A three-wire booster diagram is shown in Fig. 700.

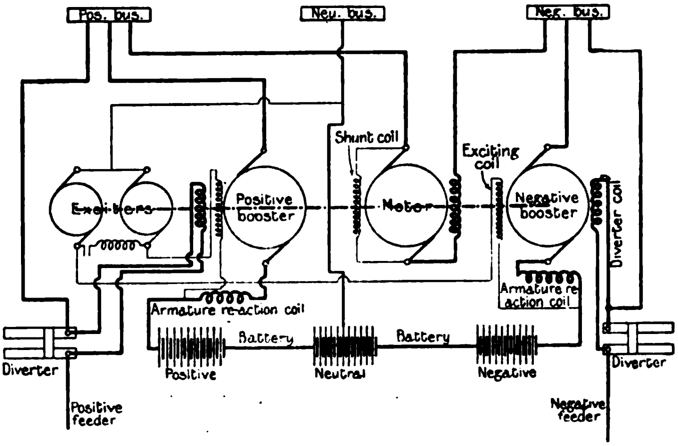


FIG. 700.—CONNECTIONS OF HIGHFIELD THREE-WIRE REVERSIBLE BOOSTER AND BATTERIES.

In three-wire working the motor is sometimes replaced by the balancer, which must be somewhat larger for this purpose than if required for balancing only.

The Lancashire Booster.—An extremely flexible and most interesting booster system is the Turnbull and McLeod "Lancashire" booster. Its object is not to provide an absolutely constant busbar voltage nor an absolutely constant generator load, since these do not appear to be desirable conditions in practice. Fig. 702 shows the connections of this machine. Coil A receives the difference between battery and busbar voltages, and causes a boosting E.M.F. of the same magnitude and opposite sign. To provide stability coil C carrying the main generator current excites a discharging boost; coil B is right across the busbars

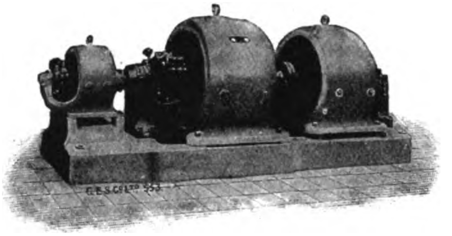


FIG. 699.—HIGHFIELD AUTOMATIC BOOSTER.

and opposes coil C. Coils B and C are, however, adjustable, the former by a rheostat J, and the latter by a diverter E in parallel with it. Coil D compensates for armature reaction. The adjustable action of the coils enables the degree of variation in generator load, or the actual busbar voltage, or the amount of charge on light loads all to be varied to meet the conditions desired, and at the same time extremely stable running is obtained. The breaker connections are interesting since the battery

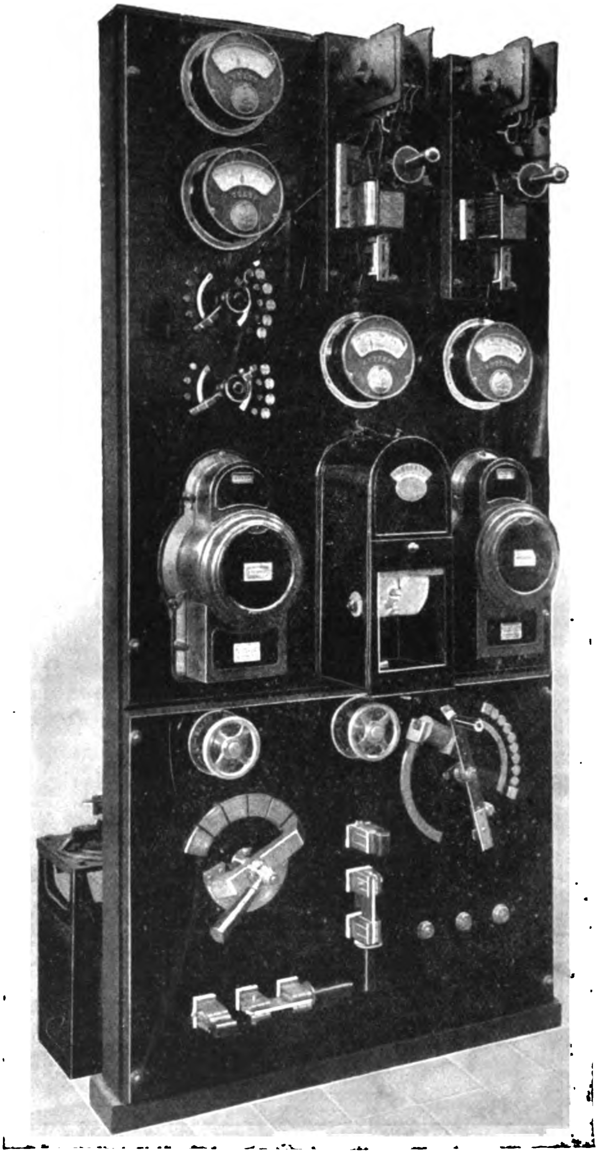


FIG. 701.—SWITCHGEAR FOR "LANCASHIRE" BOOSTER.

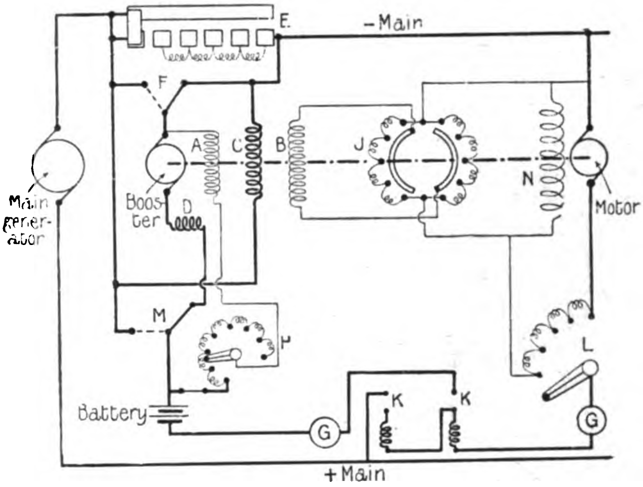


FIG. 702.—CONNECTIONS OF “LANCASHIRE” AUTOMATIC BOOSTER.

current goes through the motor breaker contacts, but *not* through its coil. This prevents the set from running away if the motor breaker comes out; the booster then cannot run as a motor. The switchboard is shown in Fig. 701

The Entz Booster.—This device consists of two sets of carbon resistances connected as the ratio arms of a Wheatstone bridge. These are compressed by a lever whose fulcrum lies between them, so that when pressure on one set is increased, that on the other is lightened, and *vice versâ.* The operation is secured by a plunger acted on by a solenoid inserted in a gap cut in the busbar. The solenoid and its curious splayed core of iron strip is seen in Fig. 704. The carbons control the magnitude and direction of current in the booster field, the field coil being placed in a position electrically similar to that of the bridge galvanometer (*see* Fig. 703).

CIRCUIT BREAKERS.

The use of circuit breakers with motors has been already mentioned, but they are most necessary and find most extensive application in protecting the various parts of a distribution system. Fuses are unreliable for this purpose, as they are hard to rate accurately, and gradually deteriorate owing to the high temperatures at which they must normally run; but they have a “time element,” *i.e.* they will be unaffected by a momentary overload unless very heavy, but will blow if a moderate one is sustained for a few seconds; and this property is of value and one which is imitated in some makes of circuit breaker.

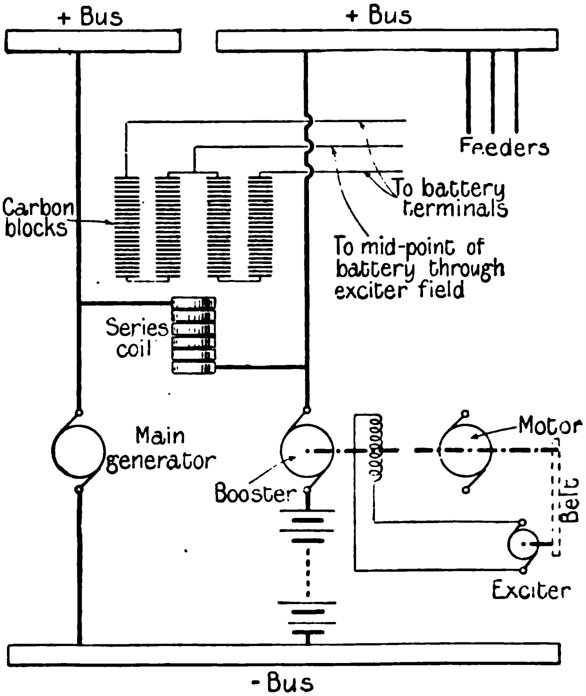


FIG. 703.—CIRCUITS OF ENTZ AUTOMATIC BOOSTER.

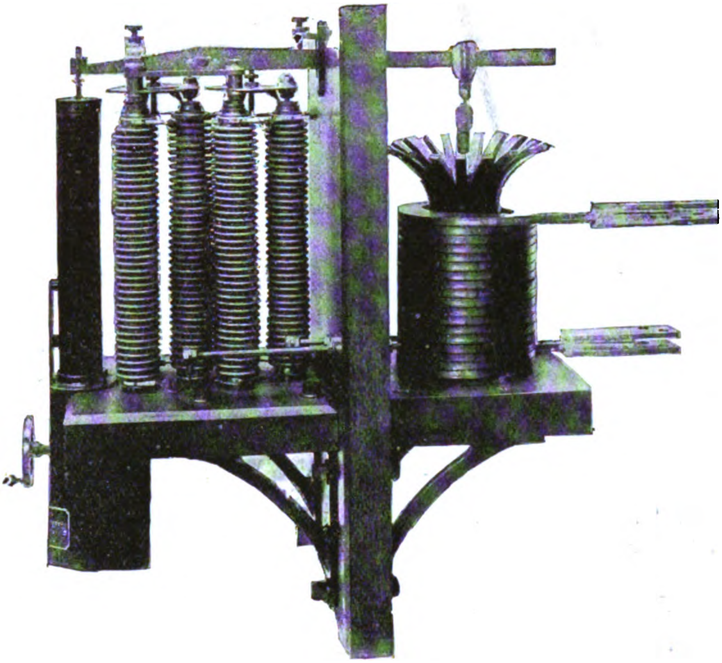


FIG. 704.—CONTROLLER OF ENTZ AUTOMATIC BOOSTER.

There are two main types of (automatic) circuit breakers :

(1) The overload ;

(2) The reverse current.

The action of these switches depends as a rule, upon the attraction of a solenoid for a plunger partially enclosed by the solenoid, and the current at which the circuit is broken may be adjusted by varying the position of the plunger (*see* p. 207).

The plunger is generally arranged in such a position that as it begins to move the force upon it increases, and the increasing speed causes it to give a very smart blow upon a release trigger. The trigger releases the main switch.

Overload Breaker.—Fig. 705 shows a single-pole "I.T.E." circuit breaker of the ordinary overload type. The ample brush contacts B C are forced up against their contact plates by the handle H (pivoted at P) by means of the toggle link L. The handle is held in this position by the retaining catch C against the action of the spring S. The series coil and plunger are contained within the framework, and in the case of an overload open the breaker by releasing the catch C, which then allows the spring S to pull the handle in an upward direction and the brushes out of contact. The final break occurs at the carbon blocks C B, which thus take the arc ; as they receive a slight rubbing motion on one another each time the switch is closed they are always kept smooth and clean.

Reverse Circuit Breaker.— Reverse current circuit breakers are generally connected between the terminals of generators working in parallel, and the station busbars,

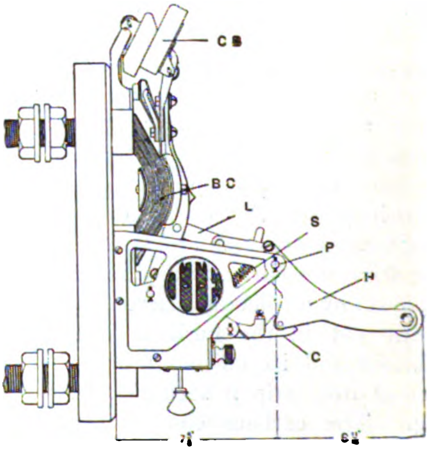


FIG. 705.—"I.T.E." STANDARD CIRCUIT BREAKER.

and are indeed the only apparatus which should be placed in this part of the circuit. Their object is to prevent any one machine from running as a motor and taking current from the line if by any chance its voltage should fall below that of the bus-bars. If a generator field failed entirely, the reverse current would be liable to cause serious damage.

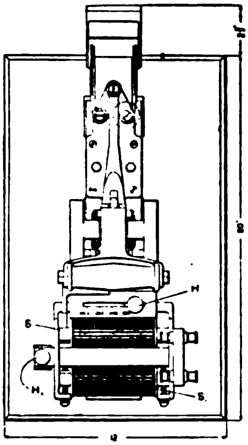


FIG. 706.—" I.T.E." REVERSE CURRENT BREAKER.

An "I.T.E." reverse-current circuit breaker is shown in Fig. 706; the reverse current or discriminating mechanism of the switch consists of two shunt electromagnets S_1 S_2 arranged to give similar poles adjacent, and a series electromagnet. The pole piece of the series magnet stands normally midway between the two shunt-magnet pole pieces, but is free to move towards the upper one, towards which it is attracted if the current reverses, and in rising releases the catch and opens the circuit breaker. It will be seen from the above that the force tending to raise the magnet core and, therefore, the time when the breaker will open, depends, not only upon the current reversed, but also upon the voltage, *i.e.* upon the power.

The breakers described are for continuous currents, but may be modified for use on alternating-current circuits.

ALTERNATING-CURRENT RELAYS.

Alternating-current circuit breakers generally consist of some form of relay controlling an electrically operated switch.

A time-element relay for a two-phase circuit, made by Messrs. Ferranti, is shown in Fig. 707. The disc shown is caused to rotate by the electromagnet seen on the left of each, the winding of which is fed from a current transformer. This electromagnet is built up of laminations, but has attached to one side of its pole face a piece of solid iron. This has the effect of causing the eddy currents induced by that half to lag behind those induced by the other half, with the result that forces of attraction and repulsion are set up between the pole and disc.

The disc on rotation winds up a suspended weight which, when it reaches a certain position, closes two contacts seen on the left-hand side of the relays. These contacts complete the circuit of the release coil of an electrically operated switch such as that described later. The time which the relay takes to operate may be adjusted by altering the position of the brake magnet, and the minimum overload at which it operates by adjustment of the weight attached. The contacts on the left hand are shown open, and those on the other closed.

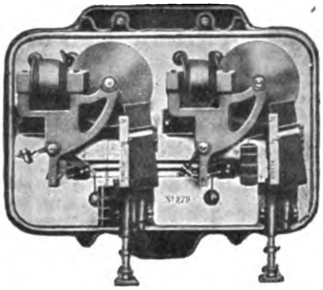


FIG. 707.—FERRANTI RELAYS.

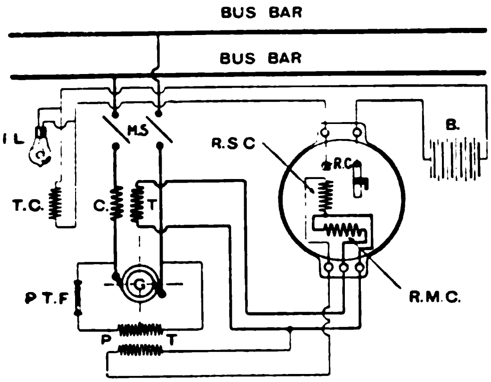


FIG. 708.—CIRCUITS OF FERRANTI REMOTE CONTROL GEAR.

M.S. = Main switch; T.C. = Tripping coil; R.S.C. = Relay shunt coil; R.M.C. = Relay main coil; G = Generator; C.T. = Current transformer; P.T. = Potential transformer; P.T.F. = Potential transformer fuse; R.C. = Relay contactor; B = Battery; I.L. = Indicating lamp.

The time which these relays take to operate will vary with the degree of overload; for instance, if the relay were set to operate in thirty seconds with a 25 per cent. overload, with 100 per cent. overload it would take only about three and a half seconds and at 200 per cent. about two seconds.

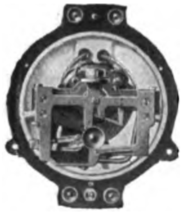


FIG. 709.—REVERSE POWER RELAY.

A reverse-power relay for alternating-current circuits by the same makers is shown in Fig. 709, and its connections in Fig. 708. It consists of a wattmeter movement similar to that shown in Fig. 669 (page 728) but placed in a horizontal position. When the power component of the current flows in the normal direction the disc tends to rotate, and by means of a projection upon this disc the weighted relay contactor R C is kept in the open position; but should the power reverse, the disc will revolve in the opposite direction, and just before completing one revolution the projection on this disc will knock the contactor into the closed position, thus closing the circuit to the tripping coil and opening the main switch. The reverse current at which the switch is to operate is set by means of a hanging weight, and the time taken by the device to operate is determined by adjusting the brake magnet.

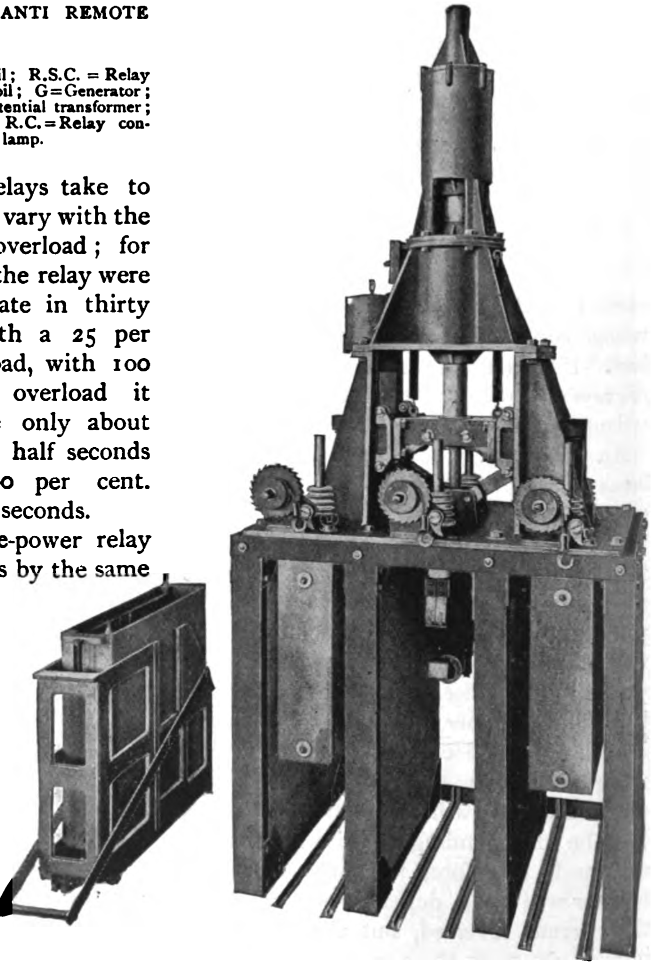


FIG. 710.—FERRANTI-FIELD REMOTE-CONTROL SWITCH.

CIRCUIT BREAKING OIL SWITCHES.

Fig. 710 shows a three-phase solenoid-operated oil switch suitable for remote control purposes, or to be operated by means of a relay.

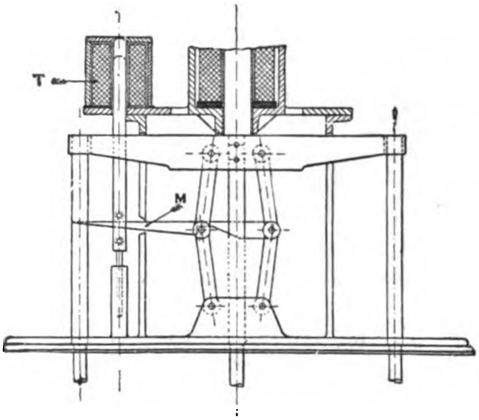


FIG. 711.—REMOTE-CONTROL MECHANISM. FERRANTI-FIELD.

The switch shown in the illustration is operated by means of two solenoids, which raise a plunger to which the bridge pieces are attached, but in later designs only one solenoid is used.

The trigger mechanism which holds the switch in the "on" position is shown in Fig. 711. A catch on the trigger M prevents the two hinge pins of a toggle joint from separating and allowing the switch to drop. The trigger may be released by an upward blow from the plunger of the tripping coil T, or, of course, by hand.

Springs seen in Fig. 710 take 75 per cent. of the weight of the moving parts when the switch is in the lower position, and thus greatly accelerate the subsequent closing of the switch.

Fig. 712 shows one end of a bridge piece, and the self-adjusting contacts K, which are attached to the mains.

The trip coil may be operated by a relay, by a switch, or by hand The hand controller is such that it prevents the switch from being accidentally closed or from being held by the hand in the "on" position should a short circuit occur.

The contacts and bridge piece are submerged in oil tanks, two of which are seen in position in Fig. 710, and one standing ready to be placed in position by a special carrier.

In the latest designs of this switch the moving parts are made largely of aluminium, and the solenoid now only requires 40 amperes at 100 volts to operate it.

SYNCHRONISERS.

It has been shown on page 528 that in order that two alternators may run in parallel their voltages must be equal, their speeds must be equal, and they must be in phase ; we will now describe some instruments which indicate to the operator when these conditions are fulfilled.

The simplest form of synchroniser is shown diagrammatically in Fig. 713, and consists of two transformers having their secondaries connected in series supplying a lamp, across the terminals of which a voltmeter is placed. The primary of one of these transformers is connected to the busbars and that of the other to the machine which it is desired to synchronise, and are so connected that only when this machine is in phase with the busbar supply do

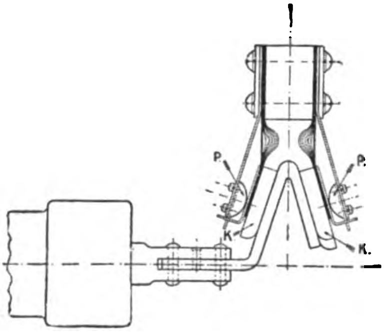


FIG. 712.—SWITCH CONTACT, FERRANTI-FIELD SWITCH.

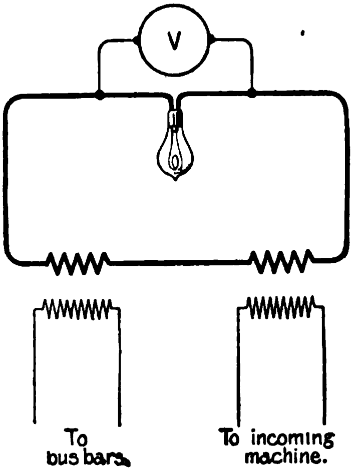


FIG. 713.—SYNCHRONISING CIRCUITS.

the two secondaries assist each other, making the lamp burn brightly. The effect when the incoming machine has not the same frequency as the busbars is therefore that the lamp fluctuates in brilliance. The operator first runs up the incoming machine and adjusts its voltage to be equal to that of the busbars; he then (keeping the voltage constant) adjusts the speed of the machine. As this becomes more and more closely that of synchronism the phase displacement slowly changes, and the fluctuations of the lamp become less and less frequent until each dark period occupies several seconds, then, at the moment of greatest brilliance of the lamp, the incoming machine is switched on to the busbars.

For Three-phase Circuits.—Three lamps are sometimes used connected as in Fig. 714 to the busbars and incoming machine (through transformers); when synchronism is obtained, the one lamp is extinguished and the other two are at full brilliance.

When the machines are out of step the lamps become dim in rotation, the direction of rotation depending upon whether the machine is too fast or too slow.

Rotary.—In a very ingenious synchroniser by Messrs. Everett, Edgecumbe and Co., the busbar voltage is led to the stator of an induction motor, and that from the incoming machine to the rotor. If the E.M.F.s are in phase the resulting fields will rotate at the same speed and the pointer attached to the rotor will experience no torque; if, on the other hand, the one lags behind the other the pointer will be moved from its central position, its direction depending upon whether the incoming machine is too fast or too slow. A synchronising instrument depending upon the principle of the frequency meter has been shown on page 301.

LIGHTNING ARRESTERS.

Where overhead lines are used it is necessary to provide for the discharge to earth of potentials higher than that for which the line is intended and for which consequently the insulation of the various apparatus connected is insufficient. The chief sources of trouble are: (1) Lightning,

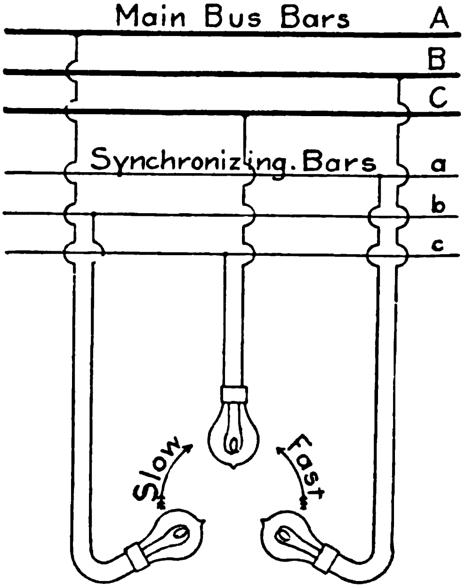


FIG. 714.—THREE-PHASE SYNCHRONISING CIRCUITS.

either directly striking the line or indirect discharges due to direct discharges near the line. A direct lightning stroke is exceedingly rare, and cannot be warded off in any known way. Indirect discharges are frequent, and so also are accumulations of static charge from the atmosphere. These can be met. (2) Surges* caused by the breaking of the circuit, and due to the collapse of energy, stored in the form of a magnetic field around the wire, into the circuit. The voltage and frequency set up from this cause will depend upon the current flowing at the instant of interruption and the length of the line connected. (3) Resonance (*see* page 382).

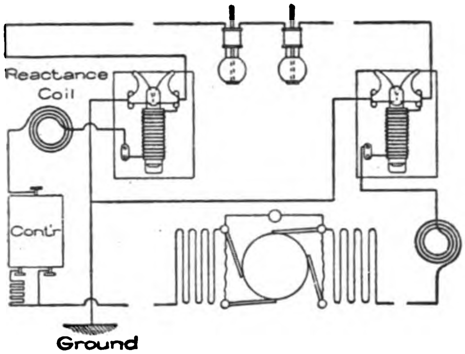


FIG. 715.—LIGHTNING ARRESTER CONNECTIONS.

The discharge of lightning consists of several oscillations of enormous rapidity and, consequently, in trying to find a path to earth through the generating or other machinery connected to the line, it will encounter great impedance in the coils and windings of the apparatus, and so frequently finds an easier path to earth by piercing the insulation of the machines.

The object of a lightning arrester is to provide this easy path to earth for high potential and generally high-frequency current, without at the same time providing a path which the ordinary working current can take. As a further protection also it is usual to place choking coils between the line and any apparatus connected to it. These coils consist of a few turns of heavy conductor, and offer to currents of the working frequency very little impedance, but to the high-frequency discharge a great deal. They therefore tend to make the latter take the path through the arrester, which is connected on the line side of the coil.

The chief difficulty consists in extinguishing the arc to earth, set up by the discharge, as this arc is very apt to be maintained by power supplied from the generating station, in which case it practically constitutes a short circuit.

The Thomson Arrester.—One of the oldest forms of arrester is the Thomson. It consists essentially of two pieces of flat metal, the lower edges of which are brought close together between the poles of an electromagnet, but recede towards the top edge. Two of these are shown in Fig 715 connected to each end of an arc lamp circuit. The discharge takes place across the narrow gap, and the spark is repelled by the electromagnets and by its own heating action to the upper part of the discharge plates, where it breaks.

The Wurtz Arrester.—Another type of arrester which is largely used is the Wurtz; it is shown in Fig. 716, and consists of a number of solid cylinders clamped between two porcelain blocks. Each of

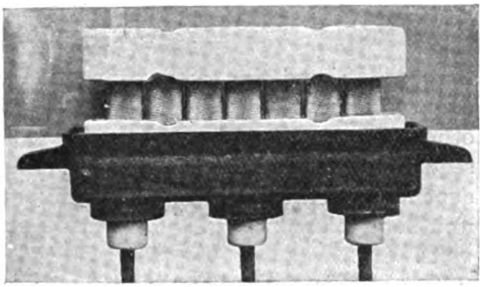


FIG. 716.—WURTZ ARRESTER.

---

*See Kenelley, *Elec. World*, Nov. 23, 1901.

these units generally contains seven cylinders. The end cylinder is connected to the line, and the earth connection is made through a resistance to one of the others, the number of cylinders (and consequently air gaps) between earth and line depending on the line voltage, an additional unit being placed in series for every 2,000 volts.

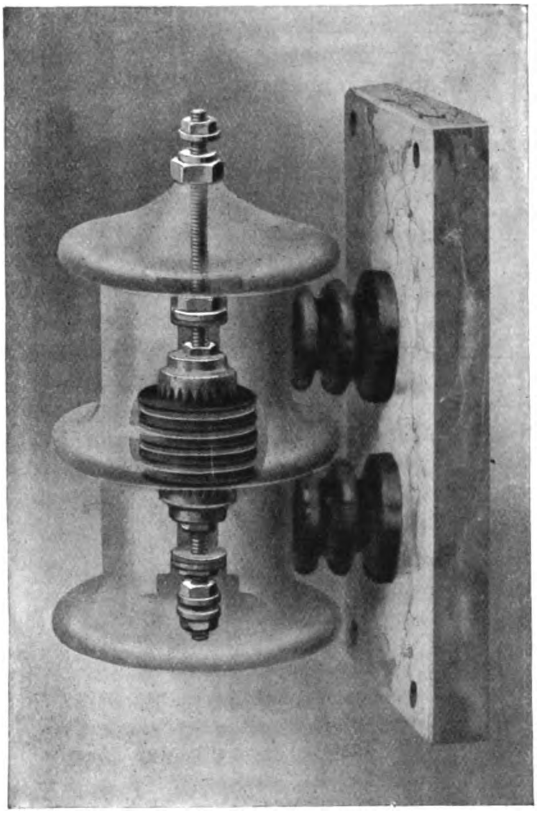


FIG. 717.—SHAW ARRESTER ("PHANTOM" VIEW).

The arc is formed from cylinder to cylinder between line and earth. The cylinders are knurled to assist the discharge, but are made of a metal which volatilises to a non-conducting vapour, and this, together with the cooling action of the metal surfaces, extinguishes the arc.

The Shaw Arrester.—This is shown in Fig. 717, and is made by the Lord Electric Company; it is built up of alternate layers of "non-arcing" and mica rings. The non-arcing rings, Fig. 718, are composed of a special material resembling carbon in appearance and are elliptical in cross-section, so that when assembled, the spacing between the peripheries of successive rings is equal.

The line connection is made to the upper terminal (Fig. 717) and the earth connection to the lower one, the discharge taking place across the inner and outer peripheries of the non-arcing rings.

Permanent Leak Lightning Arresters.—It is a frequent practice on the Continent to allow a permanent leakage of from 0·01 to 0·1 ampere to take place from the line to earth through a jet of water. The jet is made to impinge upon an inverted metallic cup connected to the line, as indicated in Fig. 719, the nozzle being efficiently earthed; the leakage through this jet of water prevents the accumulation of static charge and also provides a path for indirect lightning discharges.

The Horn Type of Arrester.—This type was first introduced in Germany,

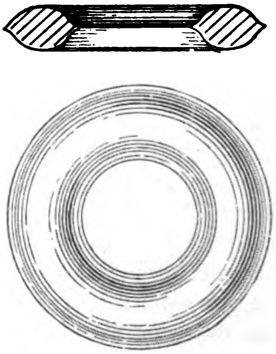


FIG. 718.—NON-ARCING RING OF SHAW ARRESTER.

and depends upon the fact that an arc started in the gap between two upwardly diverging wires, will rise, until it becomes so long that it breaks. This is due to the magnetic forces under which a looped conductor always tends to enlarge its enclosed area. The heated air, no doubt, assists this action. Fig. 720 shows three of these arresters mounted upon a pole.

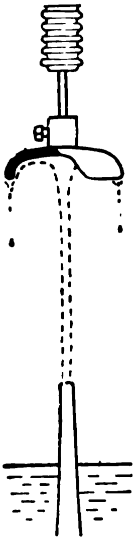


FIG. 719.—WATER LEAK ARRESTER.

Should a surge take place in the line, or should it become charged to a high potential, a discharge will cross the gap, but subsequently be extinguished, though it will sometimes hold on sufficiently long to cause trouble.

When fixing lightning arresters the earth connection must be well made, either by burying a copper plate to a depth of 6 or 8 feet in permanently damp earth, or by connecting it to an iron water main of some description. Connections from the arrester to earth should not contain sharp curves, as these would cause impedance in the circuit.

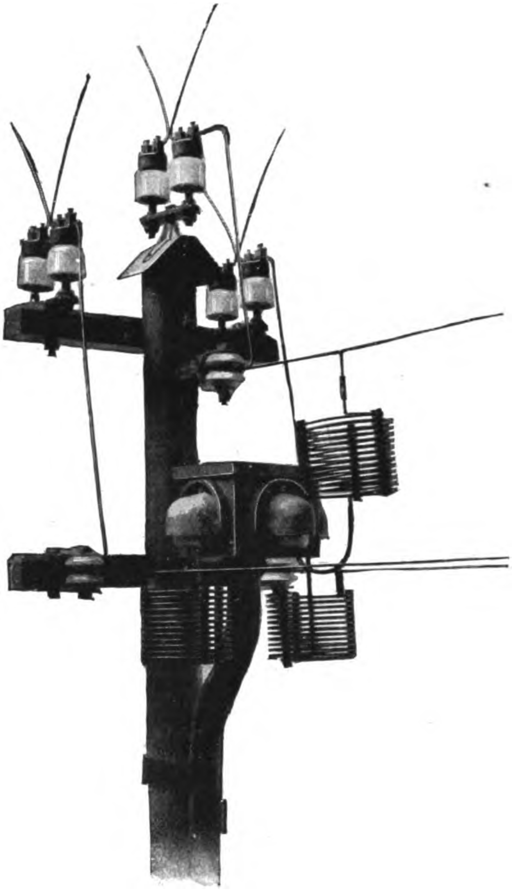


FIG. 720.—HORN ARRESTERS ON POLE LINE (JOHNSON AND PHILLIPS).

SECTION X.

TRANSMISSION AND DISTRIBUTION.

CHAPTER I.—SYSTEMS OF DISTRIBUTION.

CONTINUOUS CURRENT: ONE WIRE—TWO WIRE—THREE WIRE. ALTERNATING CURRENT: SINGLE PHASE—TWO PHASE—THRRE PHASE. FREQUENCIES—DISPOSAL OF TRANSFORMERS—COMPARISON OF SYSTEMS.

THE transmission of electrical energy, properly so-called, is usually divided into "transmission" and "distribution." While it is difficult to draw a hard-and-fast line between the two, it may be stated broadly that the term "transmission" is applied to cases in which energy is sent from one point to another only, or from one to two or more others distant from it, which are also relatively widely separated from one another. The term "distribution," on the other hand, is applied to cases of transmission from one point to many others, which are not in themselves widely separated.

The difficulties in transmitting power electrically are twofold, firstly, technical, and secondly, commercial. It is almost a truism to say that the means of meeting the technical difficulties are those which introduce commercial difficulties, and *vice versâ*. If power has to be distributed from a central station to consumers for lighting purposes, one of the first essentials, from the engineering point of view, is that the pressure at the consumer's terminals shall be practically constant, and this technical difficulty may be easily met by using conductors of so large a section that the pressure variations are brought within the desired limits. If, however, this is done, it will be found that the money expended in the cable which is laid between the central station and the consumers, will possibly reach such a high total that the interest on it cannot be met by the profits arising from the sale of the energy. If, on the other hand, the size of the cable be cut down so as to reduce the capital expenditure on it, and therefore the interest that has to be met, it may prove impossible to maintain the voltage sufficiently constant everywhere without having to resort to special means, which generally mean technical difficulties, and always involve capital outlay in a fresh direction. The business of the engineer is to obtain a minimum annual expenditure compatible with satisfactory operation. One great difficulty of a technical character in the distribution of energy for lighting purposes, is the fact that high pressures may not be introduced into ordinary houses. There are two reasons for this, one being the danger to life, and the other the impossibility at present, of making single incandescent lamps capable of taking a pressure of anything over about 250 volts. The effect of this is to limit the radius within which supply can economically be maintained at a constant pressure, with the result that, where large areas have to be supplied, means have to be adopted to provide constant pressures at various points scattered about the area, and from those points to distribute the energy within the possible radius just referred to. There are two available means to this end. One is the use of sub-stations which are fed from the main generating station through special cables, in which the varying fall of pressure due to the varying load is either of no importance or is easily compensated for, the function of the sub-station being to receive the energy and to distribute it locally at a pressure which is constant.

The other method is to substitute what are called "feeding points" for the sub-stations and to connect distributing cables, technically called "distributors," which radiate from these feeding points, the special cables which run direct from the central station to the feeding points being called "feeders." The pressure at the feeding points, in spite of the varying drop in the feeders, is adjusted by means of special devices at the central station. Either of these methods for facilitating the distribution of energy may be carried out with alternating or continuous currents, but in the case of the sub-station method, the alternating currents have a distinct advantage over the continuous ones, in that the latter involve rotating machinery, whereas with alternating currents, stationary apparatus in the form of transformers may in many instances be made to suffice. These usually require no attention and are relatively less costly than the rotating continuous-current machinery, thus effecting an economy on two counts.

Where the feeders are very long the operation between generating station and feeding points may be termed transmission, and that between feeding points and consumers, distribution.

There are two main reasons for transmitting electrical energy from a generating centre to points of utilisation instead of generating it at the places of utilisation. (1) The concentration of the total requirement on to one generating centre permits the use of larger machinery than would be possible in isolated plants, and large units are more economical than small; moreover, supervision and other attendance charges are economised. (2) Local conditions, such as a waterfall, cheap fuel, or abundant water, may make a certain site excellent and economical as a generating centre, but it may not be at the same time a suitable spot for the utilisation of the energy.

The voltage of supply exerts a vital control on the distance to which a supply can be distributed economically, or, in other words, on the radius of the circle which a central station can supply.

The following relations are important in this connection, the symbols bearing the meanings given below:

W = total watts supplied.
L = total distance or radius.
R = total resistance.
C = current.
w = watts per unit length of street, etc.
r = resistance per unit length of conductor.
V = voltage employed.

There are the following cases to consider: (*a*) where the power to be supplied is fixed in amount and the annual loss is fixed; (*b*) where the power to be supplied is proportional to the length of main and the size of cable is assumed to be fixed; (*c*) where the conditions are as in (*b*), except that the size of main is undetermined and only the total weight of copper and percentage waste are fixed.

Case (*a*) loss is $C^2 R \propto \frac{W^2}{V^2} r L$

Therefore $L \propto$ power lost $\times \frac{V^2}{W^2 r}$.

Here, if the size of the cable fixed, the distance to which W watts can be supplied is proportional to the square of the voltage, since the loss, W and *r*, are all three constant. If, however, the size of cable is not fixed, but only the total weight of copper to be used, and we call this G, further calling the resistance of a bar of unit length and unit sectional area s, and the area employed a, we have

$$r = \frac{s}{a} \text{ and } a = \frac{s}{r} \text{ while } G \propto La;$$

hence $$G \propto L\frac{s}{r} \text{ or } L \propto \frac{Gr}{s} \qquad (1)$$

Further $C^2 R$ and W are both constant; therefore

$$C^2 R = m W \text{ or } \frac{W^2}{V^2} L r \propto m W$$

where m is the fractional loss allowed; and also $r \propto \frac{m V^2}{W L}$, which combined with (1) gives

$$L \propto \frac{G}{s} \times \frac{m V^2}{W L} \text{ or } L^2 \propto V^2 \times \frac{G m}{s W}.$$

Under these conditions then, the distance is proportional to the voltage.

In case (*b*) let p be the price per watt for unit time, then $W = wL$, revenue $= pW$ and

$$C^2R \propto \frac{w^2 L^3}{V^2} \times rL \propto \frac{w^2 r L^3}{V^2}$$

if the loss in transmission is fixed at m as before;

then $$m = \frac{w^2 r L^3}{V^2} \times \frac{1}{w L}$$

or $$m V^2 = w r L^2$$

and here again $$L \propto V.$$

Case (*c*) is similar to the last down to the point $m V^2 = w r L^2$. Then substituting from $r = \frac{Ls}{G}$ we have $V^2 \propto L^3$ or $L \propto V^{\frac{2}{3}}$.

The examples are instructive as indicating the effect of varying the voltage under various conditions, and examples may be noted in that (1) W has in practice a fixed value in most waterfalls, (2) the efficiency or ratio of loss to power generated may be usefully given arbitrary values, and finally (3) the total weight of copper used may be determined by the capital available for its purchase. More important considerations are dealt with below.

The transmission of energy over long distances is a modern development of the earlier achievements in distribution of power for lighting, and we shall therefore first discuss the principal details of distribution systems, and then show how these details are modified in transmission schemes.

CONTINUOUS CURRENT. ONE-WIRE DISTRIBUTION.

This has only one regular application, and that is to the operation of arc lamps. From the very nature of it all the utilisation devices must be connected in series with each other, and the current be the same throughout the circuit. Further the line (the conductor) must form a closed circuit, and, leaving the power house in one direction, pass from lamp to lamp and work its way round until it arrives at the power house again. As a system of transmission, however, it has valuable features as will be found outlined under "Transmission."

TWO-WIRE DISTRIBUTION.

Until recent years this was the almost exclusively used system. In it all utilisation devices are connected in parallel with one another. It is regularly employed in practice for supplying private consumers with light by either incandescent or arc lamps, for public lighting by the same means, for power consumers and for tramways and railways. For lighting incandescent lamps, steadiness of voltage is of the first importance. For arc lamps the same degree of steadiness is not demanded, while for power users (motors in factories, on tramcars, etc.) the permissible variation is much greater. The generators are, in consequence, arranged to give a constant voltage with varying current, or even to give slightly increasing voltage with increasing current, so that at the higher currents the increased drop in the cables may be compensated for, and the consumer thus given a constant pressure. It can hardly be too much emphasised that what is called a constant pressure is in reality only constant within definite limits, generally four per cent. of a declared value. The system demands a very heavy expenditure on copper as compared with a series distribution (*see* page 690) of the same power, but the circuits are safer than the series, owing to the employment as a rule, of lower pressures.

The system is employed with both alternating and continuous currents, and the pressures are classed under either "low tension," * "high tension," or "extra-high tension." "Low" tensions range from 0 to 250 volts, "medium" from 250 to 650 volts, "high" from 650 to 3,000 volts, and "extra high" from 3,000 volts upwards.

THREE-WIRE SYSTEM.

In order to enable a higher voltage to be used and thus to increase the output of given mains, without lowering their efficiency, lamps might be arranged in groups in series parallel but for the difficulty of meeting the demand for small light units. The system known as the Hopkinson three-wire system, shown in Fig. 721, was adopted as a compromise. It requires less than half the copper to transmit a given power to lamps of a given voltage which would be required by the two-wire system.

In the arrangement shown two generators, each of 100 volts, are employed, connected in series between the "outers" of the three-wire distribution system, a "middle" or "neutral" wire being connected to the point between the two generators. The lamps are connected between one outer and the neutral wire. The middle wire is earthed in order that the potential above earth may not be more than 100 volts at any point.

If an equal number of lamps are connected on each "side" of the system, as shown, current will flow along the outer A B, then through the lamps to the neutral wire, and then through the second set of lamps to the outer C D. If the two sides were unequally loaded the middle wire would carry the difference to or from the generators as the case might be. Suppose that in Fig. 721 the five lamps on the A B side were switched on, and each took ·6 amperes, making a total of 3 amperes being supplied by generator 2. If there were only three lamps in use on the C D side they would require only 1·8 amperes, leaving a balance of 1·2 amperes not required by them, and this current would therefore return to generator 2 by way of the middle wire. Thus the lamps on the lightly loaded side will not be overrun.

It is almost universal practice to make the cross-section of the neutral wire half that of either of the outers.

When the difficulties in the way of the manufacture on a commercial scale of reliable high-voltage lamps were overcome, three-wire systems were laid down with 440 volts between the outers, thus still further reducing the amount of copper required for a given load.

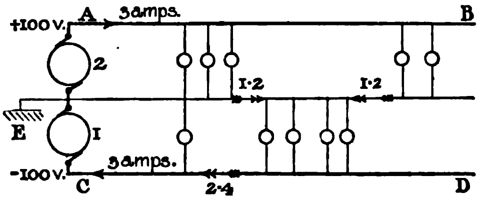


FIG. 721.—PRINCIPLE OF THREE-WIRE SYSTEM.

The working conditions of the three-wire system are best illustrated by an example:

Suppose a system with two generators, each giving 200 volts, the common terminal being earthed. The resistance of each outer is 0·013 ohm, and of the neutral 0·026 ohm. The load is such that the posititive outer carries 300 amperes, the negative 240 amperes, and the neutral 60 amperes. A 4 per cent. drop in voltage is allowable. It is required to find how the voltage is distributed.

---

* An old but still-used synonym for voltage.

Drop in + outer $= 0{\cdot}01\dot{3} \times 300 = 4$ volts
∴ Voltage at + terminal of lamps $= 200 - 4 = 196$ volts
Voltage drop in neutral $= 0{\cdot}02\dot{6} \times 60 = 1{\cdot}6$ volts (nearly)
∴ voltage at lamps between neutral and earth. $= 1{\cdot}6$ volts
Voltage at − terminal of lamps $= -200 + (0{\cdot}01\dot{3} \times 240)$
$= -196{\cdot}8$ volts.

Thus it will be seen that the pressure across the lamps on the positive side is $196 - 1{\cdot}6 = 194{\cdot}4$ volts, while on the negative side it is $1{\cdot}6 - (-196{\cdot}8) = 198{\cdot}4$ volts, so that the available voltage at the lamp terminals on the lightly-loaded side is actually raised by the drop in the neutral, a point often lost sight of.

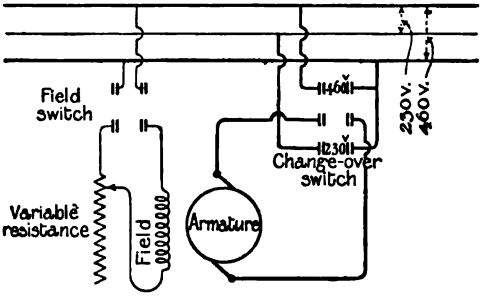


FIG. 722.—SPEED CONTROL FROM THREE-WIRE SYSTEM.

For continuous-current distribution the three-wire system is almost universal, and it is sometimes used for single-phase alternating supply.

The distinction between a three-wire and three-phase system should be carefully noted, for students are sometimes apt to confuse them. The former is merely a method of distribution, but in the latter system there are three absolutely distinct currents, each generated in a separate winding by its own E.M.F., and each being a unit in itself and capable of being used as a single-phase current, and distributed, if necessary, on the three-wire system.

Balancers.—By the use of a balancer (*see* page 750) one generator of voltage equal to that across the outers may be used instead of the two at a low voltage. The balancer should be capable of taking about 15 per cent. of the maximum current of the generator.

Sometimes a battery instead of a balancer is used in conjunction with a single generator,* but space does not permit of detailed descriptions of this and other variations.

THE FIVE-WIRE SYSTEM.

The principle of the three-wire system has been carried farther and applied in the five-wire system, in which it was expected that a still greater saving in copper would result. In practice, however, it was found that the difficulties of pressure regulation with a continually varying load, necessitated such elaborate balancing machinery and large mains that the system was not so economical as the three-wire system, and it has therefore been seldom adopted for lighting loads.

An instance of its successful application to railway work, however, will be given later in this book, and for machine shop driving, five or other "multi-wire" systems are useful, as they permit of very wide speed variations without excessive waste in resistances.

MULTI-WIRE SYSTEMS.

Speed control of motors when a multi-wire system of distribution is employed, is effected by varying the voltage both of the armature and the field, the speed of the motor being, of course, increased when the voltage across the armature is increased. The connections for varying the speed of a motor supplied by a three-wire system are shown in Fig. 722, in which the voltage across the outers is 460, and therefore between outer and neutral 230 volts. The motor is first switched on by means of a starting switch with no resistance in the field, and 230 volts across the armature; this causes it to run up to its lowest running speed. This speed is then increased by inserting resistances in the field until all the resistance has been inserted in the field, when the change-over switch is thrown over, putting a voltage of 460 across the armature, the resistance being at the same time taken out of the field; this then gives another speed without resistances, which can be again raised by inserting resistances in the field until a maximum speed is attained. In practice the switches would not be separate, but would be contained in a controller which would make the necessary field and armature connections.

---

* *See also* page 751.

It will be readily seen that by using a system of distribution, having several different voltages between its conductors, more economical speeds can be obtained from the motor, since there will be less need to use field resistances. Such a system is shown in Fig. 723, in which it will be seen that the main generator supplies at 250 volts, and that across these mains is connected a machine which is a type of balancer, and which, as it were, divides this voltage up so that various connections may be made to the brushes of the motors, and thus different voltages supplied to them. The arrangement shown gives six different stages, so that very little field regulation would be required.

These multiple voltage systems, though economical inasmuch as the motors do not waste power in resistances, have some disadvantages; for evidently the auxiliary machinery will be expensive, as will also the extra mains, for the intermediate wires, unlike the neutral of a three-wire system, *may* be called upon at times to take the full load and, consequently, must be of sufficient cross-sectional area to do so.

If the motors are only going to be run at those speeds given by the various armature voltages, standard shunt-wound machines may be used, but if intermediate speeds are to be obtained by field regulation, the machines must be specially designed to run sparklessly and, consequently, will be dearer than standard machines. Again, if the motors are required to give a constant power at a variable speed they must necessarily be heavy for their output, for the power of a motor is proportional to the surface speed of its armature and, consequently, when called upon to give its full power at a low angular velocity, its armature must be large; yet it must be capable of standing the mechanical stresses set up when running at full speed. These conditions again tend to produce an expensive motor, and when very wide ranges of speed variation are required it is generally more economical to produce some of the speed variations by means of mechanical speed-changing devices, and thus reduce the range through which the speed must be varied electrically; unless, as is sometimes the case, the "handiness" of electrical control warrants the extra expenditure on the motor.

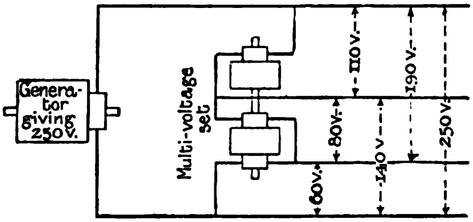


FIG. 723.—CIRCUITS OF MULTI-VOLTAGE SYSTEM.

ALTERNATING CURRENT.

The systems of distribution of electrical energy by means of alternating currents, in use, are many and varied, but with very few exceptions they are essentially either single-phase, two-phase or three-phase systems, such as those explained in Section VI. (*see* Chapter IV. therein), modified to a greater or lesser extent.

SINGLE PHASE.

The single-phase system possesses few advantages besides that inherent in all alternating-current systems, namely, that its voltage may be altered by means of simple transformers ; while it possesses the disadvantage that motors supplied from it are not self-starting unless provided with special apparatus. It is, however, very largely used in England, having been installed in most cases at a time when lighting by arc lamps was the chief consideration, and before the invention of the induction motor had demonstrated the advantages of a polyphase supply.

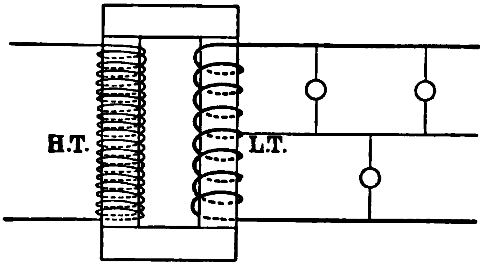


FIG. 724.—TWO-WIRE TO THREE-WIRE TRANSFORMER.

The three-wire system of distribution may be used for supplying lamps in conjunction with a single-phase supply, as with a continuous-current system, and will effect a similar saving. In the case where transformers are used to supply the distributing mains, two generators will not be necessary, but the transformer may be made to balance the three-wire system.

The connections for such a case are shown in Fig. 724, in which, for the sake of clearness, the high-tension and low-tension windings are shown wound upon different limbs of the transformer. The middle wire of the three-wire system is connected to the middle point of the secondary winding of the tranformer, as shown in the diagram, and the balancing action of the transformer is as follows :—

The secondary of the transformer acts as two transformers (each wound for the lamp voltage) connected in series but each exerting its demagnetising effect (*see* page 406) upon the same iron core. Suppose, for instance, a lamp is switched on in the top circuit, current will circulate in the top half of the secondary and exert a demagnetising effect, causing the primary to take more current ; the lower half of the secondary will have no effect. If now a lamp in the lower circuit is switched on, the same *current* will flow in series through both lamps and the whole of the secondary, thus doubling the demagnetising effect and the primary current. The effect of an unbalanced load then, is to increase the current in one-half of the secondary and thus the total demagnetising effect, and consequently, primary current.

POLYPHASE.

The discovery by Ferraris in 1885 of a rotating magnetic field produced by the combination of two or three alternating currents, gave an immense impetus to the use of alternating currents; for it was presently followed by the invention of the induction motor, which enabled alternating-current supply to compete with continuous-current supply for power purposes, by providing the former with that which had hitherto been its great need, namely, a self-starting motor.

This advantage of a self-starting motor could, however, only be secured by the use of a polyphase system, and such systems were at the time rare, though they had been used to some extent for reasons mentioned in Chapter IV., Section VI., namely, to increase the output of the generators.

The possibility of transmitting power at a high voltage by means of polyphase currents, transforming it down to a low voltage by means of stationary transformers, and using it in induction motors, now brought the polyphase system into great prominence and, so soon as the induction motor had become a commercial machine, many installations were laid down on the two-phase or, as it is called in America, the quarter-phase system, notable among which was the Niagara power station in 1895.

The saving in copper to be effected by three-phase working does not seem to have been appreciated at first, and consequently, many new installations were laid down as two-phase in America and elsewhere. Indeed, though there appears to be no doubt that for power purposes the three-phase system has the advantage, yet it is by no means a foregone conclusion that it will prove the best system for low-tension short-distance work. More particularly is this so when the load is a mixed one, consisting of lighting and power, in which case voltage regulation, due to the three phases being unequally loaded, may cause trouble, and necessitate considerable expenditure upon regulating devices to bring the regulation within the prescribed limits.

TWO PHASE.

In England this system has only been used to a very limited extent, but, in some cases, stations which originally supplied only single-phase alternating current, have been equipped with two-phase machines, and the two phases used separately to supply the old lighting circuits, but combined for power purposes. This method of effecting the change from single to polyphase supply has much to recommend it, for if necessary, one set only of the coils of the two-phase machines may be used at first to supply single-phase current to the old network, and the other phase gradually loaded up until balance is obtained, each motor being, of course, connected to both phases, in which case it will tend to balance the loads by drawing most power from the lightly loaded side.

The voltage regulation will present no difficulty, as each phase may, if necessary, be regulated separately, and, as mentioned above, the old mains may be made use of, separate cables being used for each phase. This is not the case if three-phase currents are adopted, as the use of three concentric cables for three-phase currents gives rise to capacity effects which render the working unsatisfactory.

THREE-PHASE SYSTEM.

The three-phase system is not largely used in England for distribution for lighting purposes as the conditions generally met with are not such as bring out to the full its advantages; the distances of transmission are, as a rule, short, and the saving in copper effected would not generally compensate for the increased difficulty in regulation experienced with three-phase working as compared with single-phase or direct current.

For power purposes, however, it is being extensively used by those companies which generate electricity in bulk and transmit it to sub-stations, where it is transformed down and fed into the low-tension network.

The system is also used very extensively both in America and on the Continent for distributing from sub-stations, receiving high-tension three-phase current from a distant point.

The simplest load connections for the three-phase system are those indicated in Fig. 346, page 400, and though many other arrangements are possible, the one there shown is used extensively in America and on the Continent, as it is the simplest, and requires less expenditure in mains than any other system of distribution. The chief drawback to this method of connecting the load is the necessity for arranging the lighting load so that it shall be approximately balanced; or, in other words, the regulation. This disadvantage, however, is not a very serious one when the lighting load is small compared with the motor load, for the latter being connected to all three phases will, as mentioned above, help to balance the system.

Balancing Effect of Induction Motors.—Some interesting figures relating to the balancing effect of induction motors upon a three-phase circuit were given by Mr. M. B. Field in a paper read before the Institution of Electrical Engineers, in September, 1901, from which the following are taken.

GENERATOR VOLTS.			MOTOR LOAD : AMPERES.			NON-INDUCTIVE LOAD IN
Phase 1.	Phase 2.	Phase 3.	Phase 1.	Phase 2.	Phase 3.	Phases 1 and 2.
127·6	126·5	136·1	—	—	—	90
121·5	122·5	128·5	87·4	70·8	67·8	87·0

The generator and motor were both Y-connected, and the non-inductive load was connected between the phases mentioned, the general voltage drop of the alternator was not of interest, and could easily have been prevented. A three-phase system may also be automatically balanced by means of the induction regulator, described in Chapter V. of Section VII., and the connections for this purpose are given in Fig. 520, page 565.

We have mentioned above that induction motors running upon a two- or three-phase supply have a balancing effect upon the circuits, and the reason for this may be stated generally by saying that the currents induced in the rotor generate an approximately equal back E.M.F. in all the phases of the stator winding, so that the current taken from each phase of the supply will depend upon the voltage in that phase, the larger current being, of course, taken from the phases between which there exists the higher voltage.

It is obvious, then, that this will tend to balance the circuit, for if one phase is not so heavily loaded as the other, the voltage across that phase will be higher, and consequently the motor will take more current from it and less from the heavily loaded phase.

It will be readily understood then, that if several three-phase motors are run from a three-phase supply, and one conductor of the supply circuit is then disconnected from the generator, these motors will continue to run *as three-phase motors*, and if other motors are switched on to the circuit they will be self-starting although they are receiving, in the first place, only a single-phase supply, the extra phases being supplied by the motors themselves; a similar effect is, of course, obtained with a two-phase motor.

This property of the polyphase motor is of interest, for installations of considerable size are in existence in which three-phase motors are regularly run off a single-phase supply, phase-splitters being merely used to start the first few motors. In a case of this description in which two-phase motors are run off a single-phase supply there will be found to exist about 0·8 of the full voltage across the disconnected phase.

Star Connections. — Another arrangement of connections with a three-phase supply is that shown in Fig. 725, in which it will be seen that a "neutral" wire is run from the common junction of the generator along with the usual three wires. This neutral wire practically does for the three-phase system what the neutral or middle wire of a three-wire system does for that system.

Suppose, for instance, that standard 220-volt lamps are to be used, the voltage in each winding of the generator will be 220 volts, and the voltage between lines 220 × $\sqrt{3} = 380$, and this higher voltage will be available for motor work (instead of the 220 volts available if only three wires were used) with the consequent saving in mains. In fact, under equal conditions as to power transmitted, voltage, and loss in the line, the weight of copper needed for this system and for the continuous-current three-wire system is approximately equal, although theoretically the three-phase system should have a slight advantage. The neutral wire also has a balancing effect similar to that of the mid wire of the three-wire system.

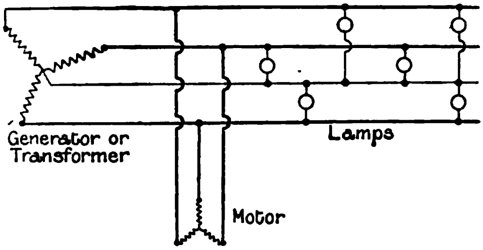


FIG. 725.—THREE-PHASE FOUR-WIRE CIRCUIT.

Other Connections.—Another method of avoiding the difficulty of regulation, which has been largely made use of in America, is to connect all the incandescent lamps across one phase of the system, and simply keep the voltage of this phase constant by regulating the field of the generator. The other phases are allowed to vary with the amount and character of the load, without any attempt being made to regulate them, and are used for running motors and arc lamps which do not require a constant voltage.

In connection with this arrangement, of course, a three-wire system may be used, fed from the regulated phase, in which case the arrangement will be as shown in Fig. 726. The plan has the advantage of being a simple one as regards regulation, but in cases where the lighting load was considerable, the three-phase generator would have to be used to a large extent as a single-phaser and, consequently, its efficiency would be lowered and, at the same time, the mains would not be made full use of.

FREQUENCIES.

The frequencies in use with alternating current supplies are various, ranging from 133 ∿ to 15 ∿, but the frequency most common at present in Great Britain is 50 ∿. It is interesting to note that the early alternating current supplies were at a high frequency, generally 100 ∿ or slightly over, because for arc lighting, which was their sole object, the high frequency gave a steadier light than a lower one would have done.

Since these early installations, however, the frequencies adopted have been steadily going down until, as mentioned above, the usual frequency in Great Britain is 50 ∿ for ordinary purposes and 25 ∿ for power purposes. In the United States a frequency of 60 ∿ is common for lighting, and 25 ∿ for power, while on the Continent many frequencies between 40 ∿ and 50 ∿ are found. Messrs. Ganz and Co., of Buda Pesth, having about the

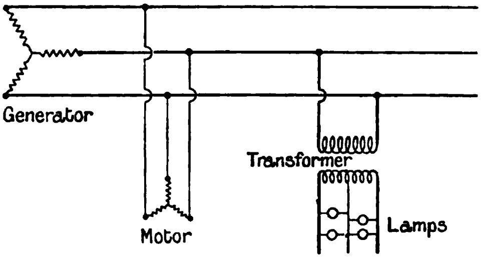


FIG. 726.—THREE-PHASE SYSTEM, ONE PHASE ONLY REGULATED.

year 1880 decided that 42 ∾ was the lowest frequency from which arc lamps could be satisfactorily run, made that their standard, to which they have adhered ever since. Glow lamps may be run without flickering from a supply of 22 ∾, but below this they will show a slight flickering. Frequencies below 20 ∾ are very rare, and are only used for single-phase railway work, in order to reduce as much as possible the iron losses in the motors and the "skin effect" in the conductors set up by the heavy currents employed.

DISPOSAL OF TRANSFORMERS.

There is another point in connection with alternating-current supply which calls for consideration, and that is the disposal of the transformers, if such are used. There are, of course, two ways in which they may be placed—they may be placed separately in small transformer pits under the streets and in consumer's houses, or they may be grouped together in substations. The choice will depend entirely upon local conditions. As a general rule it may be said that in large towns where the consumers are contained within a small area, the sub-station arrangement will be most suitable, as large transformers may then be used, and thus high efficiency, small no-load losses, and good regulation may be secured.

In districts where the consumers are scattered it is generally best to use small transformers, and place them as close as possible to the point of consumption, the transformers being, of course, supplied with high-tension current. In this way a considerable saving will be effected in mains, and the cost of the sub-station and attendance are, of course, eliminated; but, on the other hand, the cost of the transformers is considerable, as are also the no-load losses, owing to the fact that the transformers must always be in circuit.

COMPARISON OF SYSTEMS.

Upon comparing the alternating current systems of distribution mentioned above it will be seen that, other things being equal, the amount of copper required to transmit a given power is less in the three-phase case than in the two- or single-phase cases, and is equal in these last two cases (since the two-phase is only a combination of two single-phases) the ratio being about 1 to 1·33. This, however, is not by any means a comparison of the cost of mains for the systems, as the stresses upon the insulation of the cables which have to be used in each case play a very important part in the cost. Thus the three-phase system, in which the neutral point is earthed, will be less expensive than that in which it is not, because in the former case the voltage between any conductor and earth is only a little over half the line voltage while, in the latter case, the full line voltage must be provided for. Again, in the case of the two-phase system, if one four-core cable is used, it will prove cheaper than two two-core, and again, earthing the neutral point will render cheaper cables possible. (*See also* p. 397.)

In single-phase working if the mid point of the generator winding is earthed this will halve the voltage between each line and earth and give the cheapest cable, while if one conductor is earthed the cable will be a little more expensive; having no part of the system earthed further adds to the expense.

In general it may be said that the three-phase system should be the cheapest system of distribution, and that the difference between the two- and single-phase systems is not great, the latter, having if anything, the advantage in this respect.

CHAPTER II.—UNDERGROUND CABLES.

TYPES OF CABLE AND METHODS OF LAYING—CABLE FITTINGS AND BOXES—PILLAR BOXES.

Cables may be laid underground in several ways, the differences generally relating to the protection provided for preserving the insulation against damage from mechanical and chemical causes, and from damp. For example, a rubber-insulated cable may be protected with a jute or hempen braiding, or other serving, in two or more layers, and may then be drawn into iron pipes, or into earthenware conduits. It may otherwise be served outside the jute with steel tape laid on spirally in two layers, one left-handedly, and the other right-handedly, with an outside protection of yarn, the whole being treated with preservative compound, such as ozokerit, diluted with pitch, applied hot. Such a cable is said to be armoured, and may be laid direct in a trench in the ground, although it is usual to lay a narrow plank above it, so that in future excavations it may not be come upon unexpectedly by a man using a pickaxe or a spade.

Instead of the armouring and serving, a continuous lead sheath may be drawn over the insulation by hydraulic pressure in the same way in which lead pipes are formed. In some localities this may be laid direct in the ground as is an armoured cable ; but in others, vegetable acids, notably acetic acid, attack the lead, and such procedure is unsafe. Yet another method is to lay a lead-covered cable in a wooden trough, into which, afterwards, bitumen, or a bitumen mixture, is poured hot. This sets fairly hard, and the cable is said to be laid on the solid system. This system was introduced by Messrs. Callender and Co.

A system which has had wide application, but does not appear to be in favour to-day for new work, is the bare copper system. One or two varieties of this are to be found, the best known being those of Crompton and Kennedy. These differ in detail only, the main feature being the use of bare copper strip, drawn into culverts and supported on porcelain insulators at frequent intervals. The strips need to be more or less tightly strained, and considerable attention was given by the inventors of the two systems to these details, and to the means of drawing in additional strips from time to time as the demand increased.

Paper Insulated Cables.—Of recent years, the solid system appears to have grown greatly in favour, and especially with the increasing use of paper-insulated cables. For high-tension alternating-current work, paper insulated cables appear to have no equal, and their life has yet to be determined, since no appreciable deterioration has been observed in cables several years old. Paper cables, however, and their immediate forerunners, fibre-insulated cables, form a class by themselves. Paper and fibre are good insulators, but only when dry, and both materials are very hygroscopic. Their preparation as insulators consists, therefore, in very careful drying under a high vacuum, at a temperature of about 140° Fahr. in hermetically closed steel chambers. Hot oil is then admitted to the vacuum pan, immediately penetrates the pores of the insulating material, and is usually further forced in by the application of a pressure of about 20 lb. to the square inch above the atmosphere. The oil thus forced in prevents rapid absorption of moisture, but the cables need further protection of a continuous kind, such as can only be afforded by lead covering. This class of cable is known as an impregnated or hygroscopic cable. Since the very existence of the insulation as insulation depends upon the exclusion of moisture ; unceasing care is needed from the commencement of manufacture to the completion of laying to prevent the possible entrance of damp.

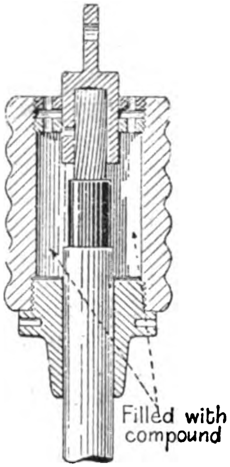


FIG. 727.—SEALING END FOR HYGROSCOPIC CABLE.

CABLE FITTINGS.

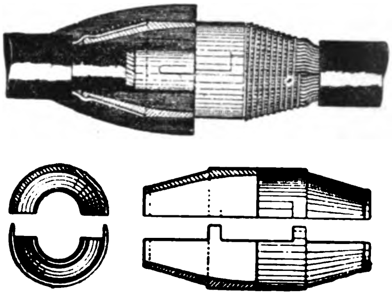


FIG. 728.—CONCENTRIC JOINT FITTING.

The lead sheath must be absolutely free from pin holes, and must be dressed hermetically over the end the moment the covering process is complete ; and if a length has to be cut, the cut ends must be again sealed without delay. Where an end has to be exposed for the purpose of connection, the porcelain sealing end, shown in Fig. 727, is used. This consists of a corrugated porcelain sleeve closed at the bottom by a flanged metal plug which is sweated on to the lead of the cable, and which screws into the porcelain. The top is closed by a bush,

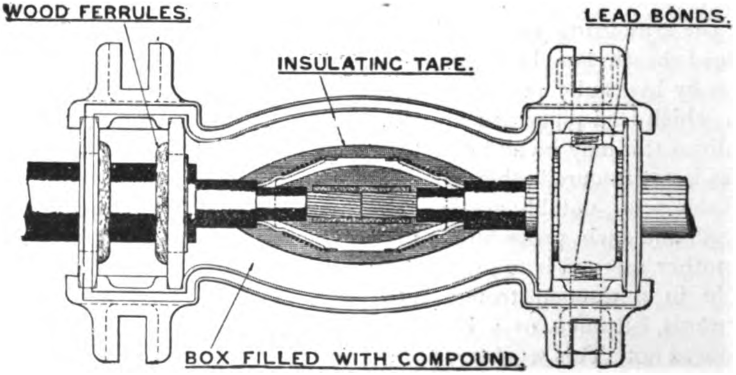


FIG. 729.—JOINT-BOX FOR CONCENTRIC CABLE.

which screws into the porcelain, and also allows the cable eye to project for connection. The space inside the porcelain is filled with compound, a mixture of bitumen, pitch, and Stockholm tar, run in hot. The cable eye sweated on to the strands, prevents the entrance of moisture above the level of the compound. Where two lengths of underground cable have to be permanently connected, joint boxes are used, and where the cables are concentric special devices have to be employed.

Concentric and Three-Wire Cable Fittings.—A concentric cable has two or more conductors arranged as concentric cylinders, separated from one another by concentric layers of insulation. The innermost conductor is an ordinary stranded one, while the strands of an outer conductor are laid side by side over the insulation of the inner, with the result that the outer is practically a tube of copper. If there are but two conductors the cable is called concentric, and if there are three, a triple concentric. It will be readily seen that such a cable is difficult to joint, still more difficult to take a tapping from, since all the outer layers must be cut to get at the innermost, and yet the continuity of all three conductors, of the three insulations, and of the lead sheath, must be perfectly restored. The continuity of the lead sheath need not be restored precisely, but its electrical continuity must be restored, as must also the continuity of

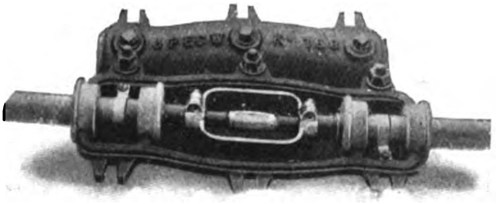


FIG. 730.—STRAIGHT-THROUGH CONCENTRIC JOINT-BOX.

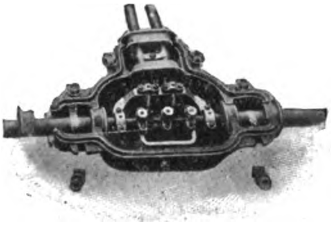


FIG. 731.—TRIPLE CONCENTRIC T-JOINT-BOX.

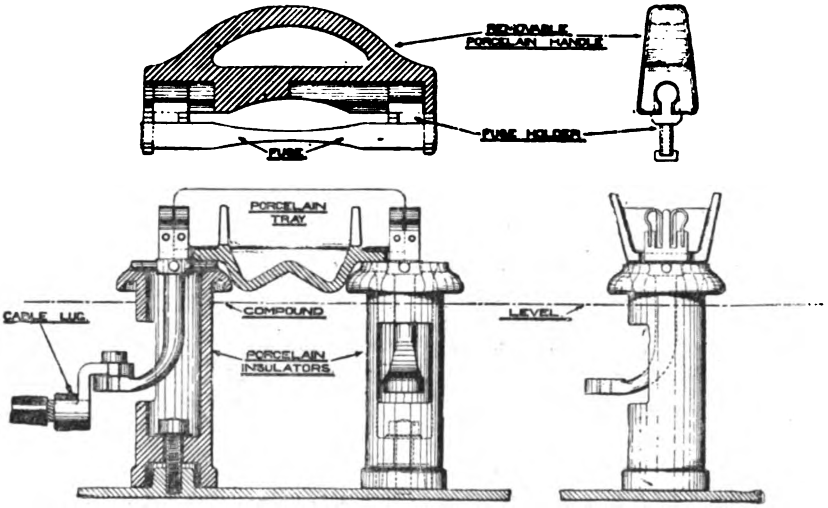


FIG. 732.—FITTINGS FOR HIGH TENSION DISCONNECTING BOX.

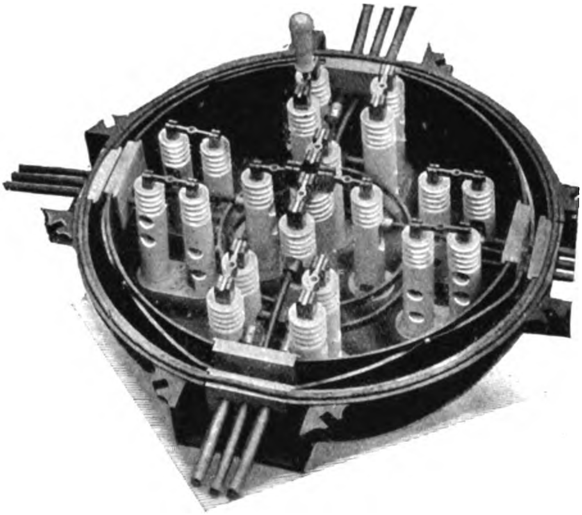


FIG. 733.—FOUR-WAY HIGH-TENSION THREE-WIRE DISCONNECTING BOX.

the water seal. The former is necessary to prevent electrolysis at the break, due to stray currents in the lead being forced to leave the lead there. A convenient jointing device for a straight through joint made by Messrs. Callender and Co., is shown in Fig. 728, applied to a concentric cable. The two inners are slipped into a brass ferrule, and soldered there. This joint is then insulated with tape, and over this a split metal shell is placed, the two ends of the shell being conical. The strands of the outers are laid up on the coned ends, and bound in position. They are then soldered, and the outer insulation restored with tape. The whole joint is then laid in a cast-iron box, and the interior of the box filled up with compound. The latter completes the seal, while the former may be used to preserve electrical continuity of the lead. The lead may have a copper tab sweated on to it, and the tab be clamped under a screw on the box. Or the box may have the special lead bond, consisting of two wedged-shaped iron clamps, forced into contact by set screws, so as to grip the lead sheath and lead washers, as shown in Fig. 729. If these are not wanted, the entrance and exit to the box are through wood ferrules. A cast-iron cover bolted on completes the arrangement.

Fig. 730 shows a joint box employed by Messrs. Johnson and Phillips, in which the centre core is jointed in the ordinary way and the outer core cut away and connected by special clamps. Fig. 731 shows a T-box for a branch from a triple concentric cable.

In many instances, the connection is not desired to be permanent, and in such cases a disconnecting, or fuse, box, is used. The cable ends are brought into a rather deep iron box, having brass fittings supported on porcelain insulators. The cable ends and their junctions to the brass fittings are below the level to which compound is poured in.

Fittings employed by Messrs. Callender are shown in Fig. 732, a special porcelain tray being used to catch the molten fuse, which would sink into the compound.

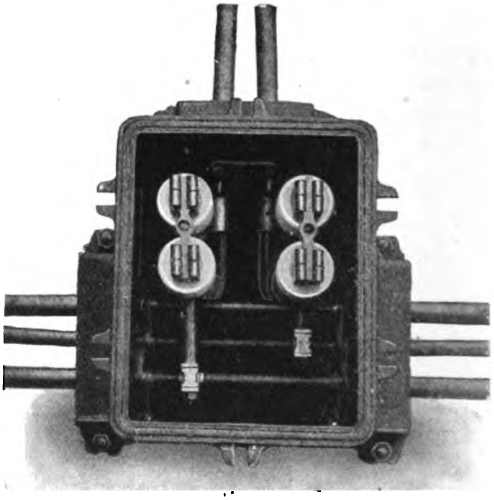


FIG. 734.—TWO-WIRE SERVICE BOX FOR THREE-WIRE SYSTEM.

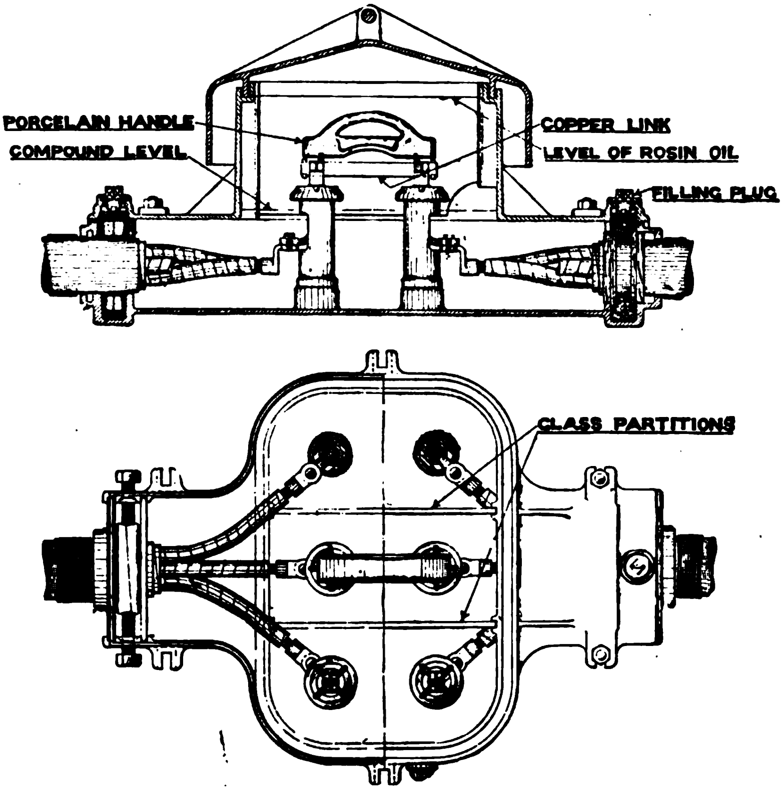


FIG. 735.—EXTRA HIGH TENSION DISCONNECTING BOX.

The walls of this tray also help to check arcing.

In place of the fuse solid copper links are sometimes employed, as shown in Fig. 733, which is a three-wire four-way box by Messrs. Johnson and Phillips. The detachable handle for removing the connecting links is seen on one link. Fig. 734 shows a box as used by the same firm for taking a branch off one side of a three-wire system.

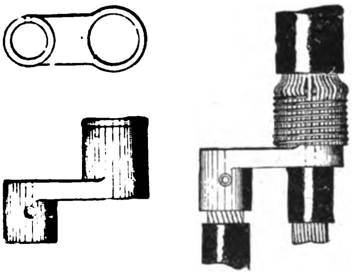


FIG. 736.—JOINT FITTINGS.

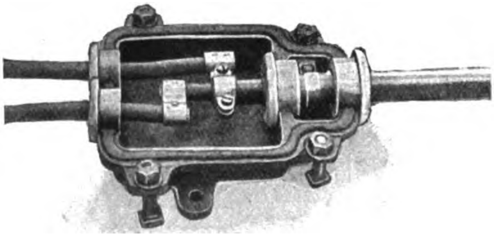


FIG. 737.—CONCENTRIC TO "SINGLES" JOINT-BOX.

High-Tension Boxes.—For tensions up to

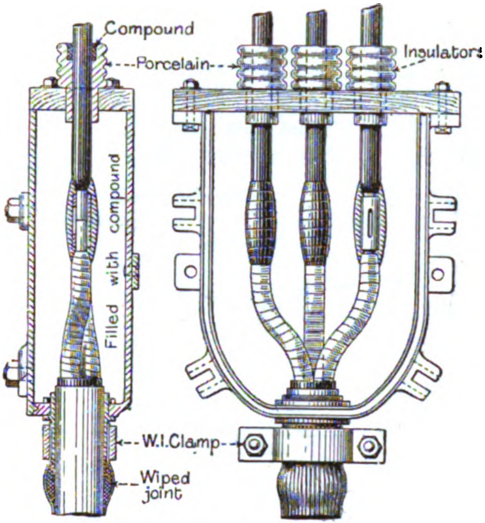


FIG. 738.—DIVIDING BOX FOR THREE CORE TO THREE SINGLES.

6,000 volts, further protection is added by submerging the parts projecting above the compound level in resin oil, and by providing glass partitions between adjacent poles or phases. Such a box for a 6,000 volt three-phase circuit is shown in Fig. 735, together with its cast-iron diving bell lid to exclude surface water.

Dividing Boxes.—It is frequently desirable, as at the entry to a building, to change over from hygroscopic concentric cables to single rubber or vulcanised bitumen cables. This is done in what is called a dividing box. A simple fitting for changing from concentric to two singles is shown in Fig. 736, and needs no explanation. It is of course employed in a box, and covered with compound.

Another simple method is shown

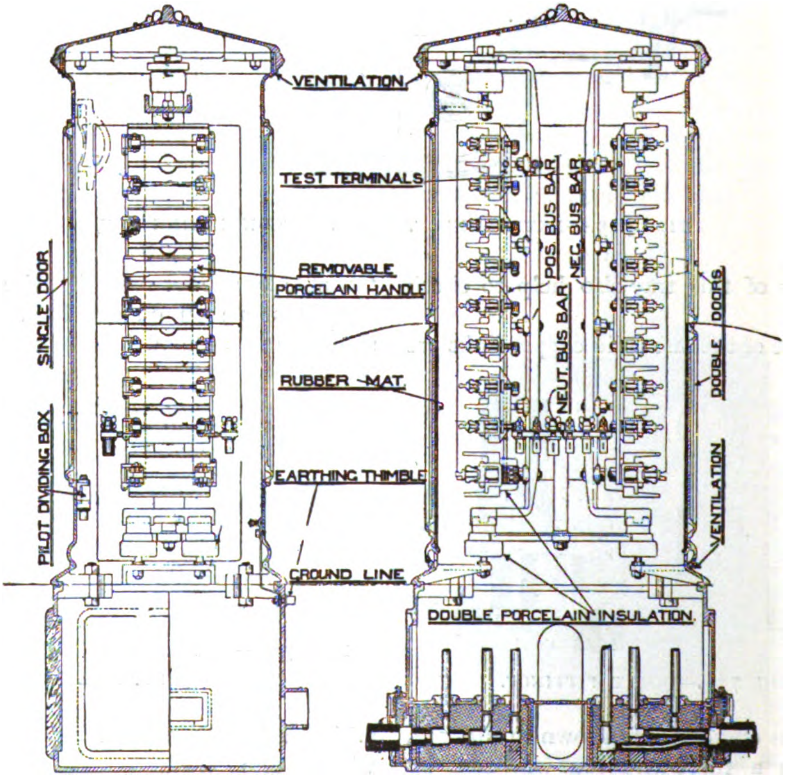


FIG. 739.—FEEDER PILLAR FOR NINE THREE-WIRE DISTRIBUTORS.

in Fig. 737. A high-tension three-phase dividing box is shown in Fig. 738, the only point needing further comment being the wiped joint between the lead of the cable and the flanged and screwed metal bush at the bottom of the box.

PILLAR BOXES.

It is frequently preferable to provide for jointing and disconnecting above the street level, so as to save lifting heavy box covers, etc. For such purposes, pillars are used, and the cable ends are brought through sealing boxes up into the pillars. A pillar for connecting nine distributors on to one feeder of a three-wire network is shown in Fig. 739. The pillar has doors on either side giving access on the right-hand side to all the negative connections, and on the other to all the positive connections. These are all mounted on porcelain insulators, which in turn are carried on heavy vertical **T** irons. The **T** irons are supported top and bottom by other porcelain insulators, bolted to the frame of the pillar, thus giving double porcelain insulation. Close inspection of the figure, and reference to what has been illustrated in the preceding pages, will make all details clear. The neutral busbar is arranged as a horizontal ring, while the positive and negative are vertical bars. The feeder is attached at the bottom of the busbars, and the distributors are connected through disconnecting links in two vertical ranges. A dividing box is provided for the pilot wire which connects this feeding point to a voltmeter at the station.

Fig. 740 gives an outside view of a pillar for a similar purpose. The neutral busbar and connections are seen at the bottom.

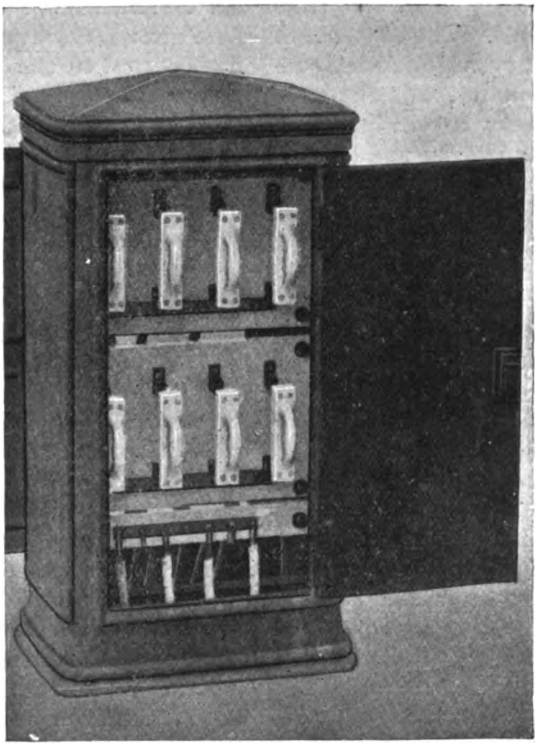


FIG. 740.—THREE-WIRE FEEDER PILLAR.

CHAPTER III.—TRANSMISSION.

METHODS OF TRANSMISSION — HIGH-VOLTAGE WORKING — THE LINE — HIGH-TENSION TRANSMISSION—THE THURY SYSTEM.

THE reasons for transmitting power from one point to another have already been referred to in some degree on page 763. The transmission over long distances is in almost all cases due to the fact that power can be generated cheaply at some point where it cannot be economically utilised. The cheap generation is generally the result of one of the following causes: (1) the existence of a waterfall of large power; (2) the production of cheap coal in large quantities; (3) the existence in large quantities of waste fuel. The existence of water powers of any magnitude is uncommon in this country, but they are turned to account very largely indeed in Switzerland, in Scandinavia, and on the continent of America. The use of coal actually at the pit's mouth has not been adopted in practice, but cheap coal is a large factor in the successful operation of several large companies in the north of England. The use of blast-furnace gas, a fuel which was thrown to waste in the most prodigal manner until very recently, is finding application in gas engines of very large size, in England, America and Germany, in which latter country especially have they been developed. The time has not yet come when this power is to be transmitted over any distance, since it at present is entirely absorbed in meeting local demands.

METHODS OF TRANSMISSION.

There are two main methods of transmitting power (*see* page 690), the one in which the voltage is kept constant, and the other in which the current is kept constant. With the former system the utilisation devices are all in parallel, and with the latter all in series. The determining factor in all cases is the cost at which the energy can be delivered per horse-power hour at the point of utilisation, and in this cost the expenditure of capital on cable plays a predominant part. Now the size of cable selected will clearly depend upon the current strength, which in turn will, for a given power transmitted, be inversely proportional to the voltage; hence, the higher the voltage, the smaller the cable that can be employed. If the power to be transmitted is fixed, and the percentage loss in the line also fixed, doubling the voltage will halve the current, and reduce in a given line the volts lost to halt of what they were before. But at the higher voltage the volts lost may also be doubled, so that the weight of the line may be reduced to one quarter of what it was before. On the other hand, increasing the distance of transmission of any power while keeping the voltage and percentage loss constant will increase the weight of copper directly as the square of the distance (*see* page 763).

The above relations hold broadly for any system, and if they were the only considerations it would appear that in every case the system offering the highest voltage would be the best. There are, however, other considerations affected by the voltage of operation, among them being the prime cost of the generators and switchgear, the cost of insulating and difficulty of maintaining the transmission line, and finally the ease and reliability of operation of the utilisation devices. Theoretically, either constant-voltage or constant-current transmission can be adopted with either alternating or continuous currents; but in practice, over say twenty miles and more, and especially when the distances exceed one hundred miles, constant potential operation with alternating currents, or constant current operation with continuous currents, are the only two alternatives. As regards alternating-current transmission, a certain latitude of choice lies between single-phase, two-phase and three-phase working, although the cases are rare in which three-phase working is not easily first. Some reasons for this have been adduced on page 399. Constant current or series working has rested for its development in the hands and on the genius of one man, M. Thury, while alternating current parallel working has received the attention of eminent engineers throughout the world. M. Thury's system will be described later on.

HIGH-VOLTAGE WORKING.

The difficulties which arise from the adoption of a high voltage begin with the generator. When values of 10,000 volts and over are reached, a silent glow discharge takes place at the surface of conductors, and if air is present ozone is formed. Occasionally even, brush discharges may take place, and with these nitric acid is formed from the nitrogen of the air. Both ozone and nitric acid are such powerful oxidising agents that no insulator such as can be used in machine construction has been found to withstand their action for long, and special construction must be followed to avoid this difficulty. The most obvious thing to do is to exclude the air, and this is done in machines by consolidating adjacent conductors and their insulation into practically solid blocks, while in transformer construction the whole apparatus is immersed in oil. Oil-immersed switches are used wherever possible, and switchboard insulation in general is effected by means of the best porcelain obtainable, liberally dimensioned.

Not infrequently the difficulty of insulating generators for the high voltages required leads to the use of step-up transformers. The latter are relatively very easy to insulate, since they may operate permanently immersed in oil, which effectually excludes moisture and air. Modern transformers are also highly efficient, so that there is little objection on the score of loss. From the high voltage side of the transformer the usual practice is to employ bare copper, mounted on porcelain supports, and in undertakings of any magnitude ample space has to be provided for the switchboard compartment, the transformer room, and the high-tension busbar room.

THE LINE.

Insulated cables placed underground are used over distances up to as much as ten miles, the voltages employed being from 6,000 to about 13,000. For distances greater than these higher voltages are desirable in order to economise in copper. The capacity (condenser effect) of insulated lines placed underground is capable of causing trouble in long lengths and at high voltages. This is owing to the high specific inductivity of the rubber or other dielectric used. Cables must, on the score of expense, be placed near together if underground, or possibly three-core or concentric cables have to be used. Overhead bare wires on poles operate with air as the dielectric, and the conductors can be spaced feet apart instead of fractions of an inch apart. The capacity of such lines is, therefore very much lower than that of underground lines. For long-distance work the invariable practice, consequently, is to use bare copper conductors supported on porcelain insulators which are fixed to poles. Up to 20,000 volts it is comparatively simple to provide the necessary insulation by porcelain insulators of the petticoat pattern, such as that shown in Fig. 741. Care must be exercised to design the poles and pole arms so as to keep the lines at a sufficient distance to prevent brush discharges between them, not only when hanging still in calm weather, but during storms and high wind.

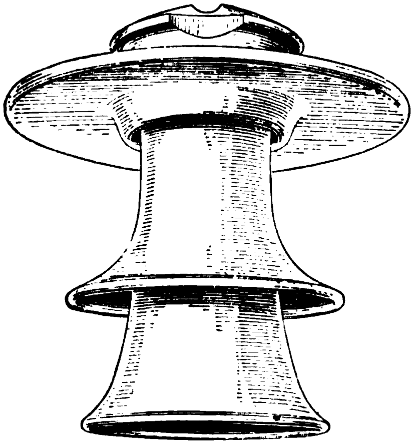
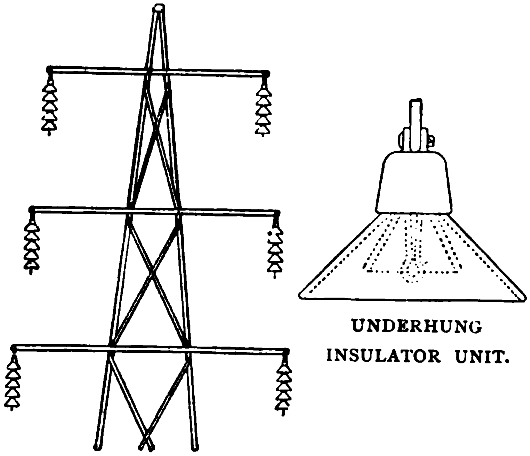


FIG. 741.—"THOMAS" INSULATOR.



UNDERHUNG INSULATOR UNIT.

FIG. 742.—POLE AND UNDERHUNG INSULATOR FOR TWO THREE-PHASE 100,000 VOLT LINES.

At voltages of the order of 30,000 and up to 60,000, difficulties are greatly increased. The insulators have to be much larger, and are made in several parts or "shells" cemented together with Portland cement. Each part is about ½-in. thick, since this is the greatest thickness giving satisfactory manufacture. Each shell can stand 60,000 volts test but should not work at above 20,000. For higher pressures multipart construction is used, and when 70,000 volts are reached modern practice tends to the use of several in series. This is carried out by suspending the conductor from the underside of the insulators, there being a short chain of insulators at each point of suspension. The method is illus-

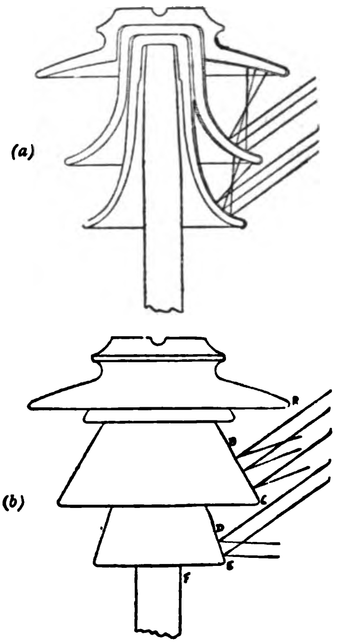


FIG. 743.—EFFECT OF RAIN ON LEAKAGE PATHS.

trated in Fig. 742. The leakage path is thus the sum of the paths over the surfaces of the individual insulators.

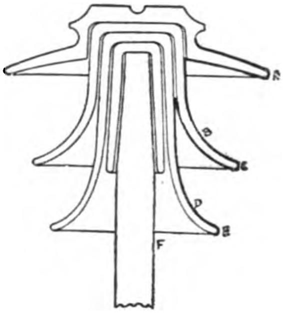


FIG. 744.—SECTION OF HIGH VOLTAGE INSULATOR.

Owing to the free suspension the line sways much more in wind than with the older type of insulator. The pole arms are therefore made much longer to keep the lines from contact with one another or the pole. The chief difficulty is the maintenance of the insulation in rain, heavy rain being troublesome, but a persistent driving mist being often more so. If the whole surface tends to become damp the leakage current may be large enough to dry off the moisture through heating as fast as it can form.

With the form of insulator having curved flanges water is liable to reach the under surfaces from spattering (Fig. 743 *a*). The form of insulator shown in Fig. 743 *b* is better in this respect. The moisture forms a high resistance leakage path as shown by the thick line on the right-hand side of the insulator in Fig. 744. This path should have sufficient resistance to keep the current low. The moisture connects the points A, C and E successively to the line potential, producing a tendency to puncture at the points B and D to the earthed pin F, or to arc to F from E. The distance from F to E must be great enough to prevent this, and the strength at B and D be increased by an inner shell, thoroughly protected from wet, on the top of the pin as shown.

HIGH-TENSION TRANSMISSION

There is a tendency to push line voltages even higher, up to 100,000 volts, and even a possible 150,000. The difficulties, however, are serious enough at 60,000, and there is some loss of energy from glow and brush, and the capacity current becomes of serious magnitude. If such pressures as 100,000 volts are to be employed, the spans from pole to pole will doubtless be much increased beyond the present practice, so as to reduce the number of insulators (*i.e.* leakage points) per mile. In order to attain to such long spans a composite wire may be used. The use of a span wire and a conductor hung from it is impossible for long spans, owing to wind pressure and snow and ice troubles. Therefore, it becomes an important problem to design composite cables of steel and copper, or of steel and aluminium perhaps, to provide a combination of sufficient tensile strength, lightness, and conductivity.

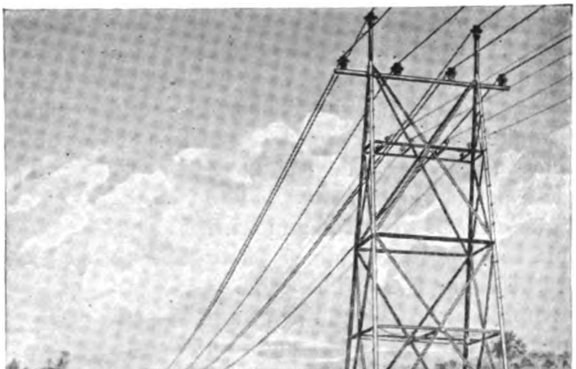


FIG. 745.—TYPICAL LINE CONSTRUCTION.

A typical line construction is shown in Fig. 745.

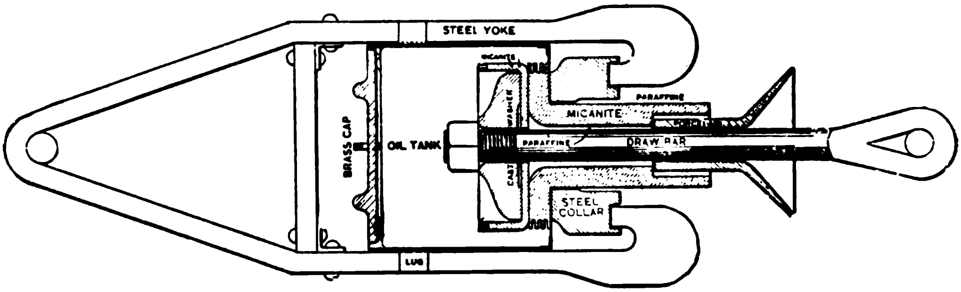


FIG. 746.—DETAIL OF STRAIN INSULATOR FOR 60,000 VOLT LINE.

One of the best examples of modern high-tension transmission practice is the much-described line crossing the Carquinez Straits in California. This waterway is about 1,100 yards wide, and in preference to using submarine cables it was decided to employ an overhead span. The usual method of suspending a copper cable from a steel span wire could not be tolerated owing to the excessive wind pressure which would arise on the large area exposed. A steel wire of sufficient section to secure at the same time ample conductivity and ample tensile strength was therefore used for the conductor. A nineteen-strand cable is used, having a total diameter of $\frac{7}{8}$ in. and the conductivity of a $\frac{1}{2}$ in. copper wire; the ultimate strength of each cable is 9,800 pounds, and the total weight of each span is 7,080 pounds. The sag allowed is 100 feet and with this tension the factor of safety in the cable is 4. The cable is anchored at each end through special strain insulators, and from the insulator it passes over grooved steel rollers carried by towers. The tension at each anchorage is 12 tons, and the downward pressure on the towers 7,000 pounds each. Anchorage is obtained by large concrete blocks embedded in the earth. The strain insulator exhibits features of considerable interest, and is illustrated in Fig. 746 in section. An examination of Fig. 746 will convey the main details of the construction, and it will be seen that the whole of the insulator employed is under compression, and that the chief factor in the insulation is micanite. In order, however, to secure freedom from creepage, which would have taken place over the surface of the micanite, the micanite is placed inside a copper tank, which latter is filled up with oil, the edges of the micanite being deeply grooved in order to increase the length of the leakage path. In order to prevent creepage from the steel draw bar, a conical porcelain tube is added, and the free space between the draw bar and the micanite is filled by running in extra hard paraffin wax. The voltage of transmission is 60,000, and, while one of these strain insulators is quite sufficient to withstand this pressure, they are used two in series, as seen in Fig. 747. In order to provide

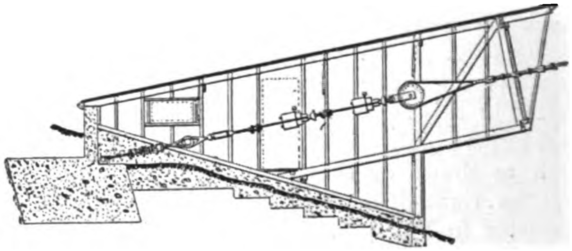


FIG. 747.—ANCHORAGE AT CARQUINEZ STRAITS.

against leakage due to rain, a wooden shelter is erected over the insulators at each anchorage. Seeing that it was impossible owing to the position they necessarily occupy, to provide against trouble by the ordinary methods of petticoat line insulators, the insulation between the cable and supporting towers is also of considerable interest. The cable rests immediately upon five rollers, which in turn are supported by a wooden saddle. The wooden saddle is entirely fastened with wooden dowel pins, and is supported on triple petticoat insulators of porcelain cemented together with sulphur and carried on a massive conical steel pin, which is also encased in a porcelain sleeve. The outer shell is 17 in. in diameter. The saddle, as will be clearly seen from the illustration (Fig. 748), shields the porcelain insulators, which are six in number from rain, a special water shed and spout being provided for the purpose. The wooden saddles are well boiled in paraffin wax. Provision is made on the tower for four cables, the fourth being a stand-by should one of the others break down. The anchorage with its shelter is shown in Fig. 747, while details of the saddle insulators may be gained from Fig. 748.

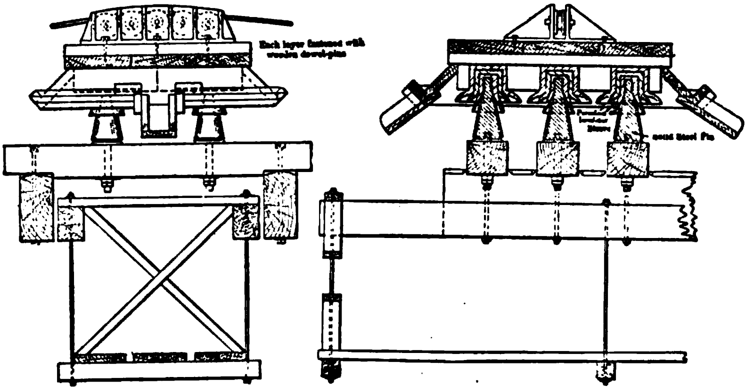

Each layer fastened with wooden dowel-pins
Porcelain Insulator Sleeve
Solid Steel Pin

FIG. 748.—SADDLE FOR 60,000 VOLT SPAN-LINE.

Another important detail in high-tension transmission is the way in which high-voltage cables are brought into buildings. The method employed for the line between Niagara and Toronto with a pressure of 60,000 volts is shown in Fig. 749;

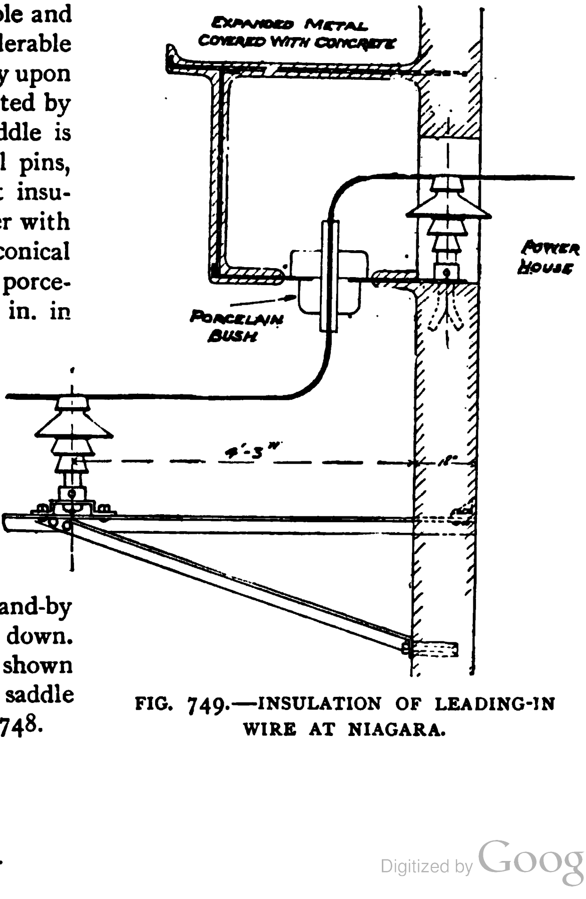


FIG. 749.—INSULATION OF LEADING-IN WIRE AT NIAGARA.

another method in use is shown in Fig. 750.

THE THURY SYSTEM

One of the most remarkable transmission systems is that which has been developed single-handed by M. Thury, and which, contrary to all others in present use, consists in arranging both generators and utilisation devices all in series. In this system, therefore, the cutting out of a motor is effected by short circuiting it, and the same process cuts out a generator.

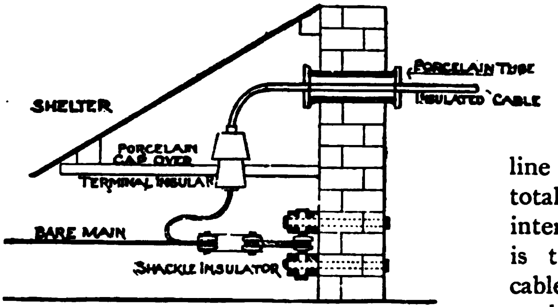


FIG. 750.—ANOTHER METHOD OF INSULATING LEADING-IN WIRES.

The generators are series wound, and before they are short circuited the brushes are rocked to the no-voltage position, and the field windings are short circuited. One important item in the reduction of expense obtained by the series system is the extreme simplicity of the switchgear; the only gear required in a generating station is an amperemeter and voltmeter for each generator, a switch for short circuiting each generator or putting it into circuit, and an automatic device for adjusting the speed of the prime mover to correspond with the load. Each generator may be designed for a maximum voltage of 5,000, and for any current that may be chosen up to say 150 amperes. The transmission line usually consists of one pair of wires only, although of course a three-wire system may be used, or, if the load increases beyond the anticipated maximum, a second circuit may be run independent of the first. There are at present some fifteen large undertakings at work on this system. The latest of these is the Moutiers-Lyon transmission over 112 miles. At the generating end there are sixteen generators arranged in four groups of four; each group of four is driven by one turbine, and each machine gives a maximum of 3,600 volts, thus providing a total line pressure of 57,600. The line current is 75 amperes, so that the total output is 4,320 kilowatts. One interesting feature of this undertaking is the successful use of underground cable, several miles being in operation at the Lyon end. The system is free from several inherent difficulties of the alternating kind; for the same stress on the insulation an alternating system can only employ 0.707 of the pressure, the capacity of the line, moreover, can introduce no difficulty, so that there is an entire absence of surging effects, and brush discharges and breakage of insulators through piercing are largely reduced. The system also gets over all difficulties such as arise from running machines in parallel with one another, and the switchgear, as stated above is of delightful simplicity. In addition there is no occasion whatever to duplicate the line for fear of insulation troubles.

SECTION XI.

ELECTRIC TRACTION.

CHAPTER I.—EQUIPMENT OF TRAMWAY CARS AND TRACK.

INTRODUCTION. CAR EQUIPMENT: MOTORS—SIZE OF MOTOR—RATING—CONTROLLERS—SERIES-PARALLEL CONTROL—REGENERATIVE CONTROL—BRAKES—TRUCKS. TRACK: RAILS—JOINTS—BONDING—THE THERMIT WELD.

INTRODUCTION.

The application of electric propulsion to tram-cars is attended by advantages which are not collectively attainable by any other means. The variations which have had commercial vogue are, horses, steam and cable. The first mentioned must yield to all the others in regard to the size of car that can be smartly handled, and to speed, while, further, in many instances, greater economy of operation can be attained by other means. Steam cars must yield to cable and electric cars in towns, on the score of quietness and cleanliness, the noise, dust and smoke having proved most objectionable, especially in residential districts. Cable cars are excellent for quietness and smoothness of operation; their chief excellence, however, is found in dealing with very steep gradients. For ordinary gradients electrical operation is superior in regard to speed attainable and in regulation of speed among other traffic, while for economy of operation electric working yields on the whole satisfactory results.

There are three methods in use for conveying power to the cars: (1) By overhead wires and a travelling contact carried by the car; (2) By underground conductors in a nearly closed conduit and a travelling contact; (3) By contacts in the surface of the road at regular intervals and a travelling contact.

CAR EQUIPMENT.

Motors.—The conditions under which a tramway motor works are very onerous. The motors must be extremely compact, so that they may be easily placed in the small and strictly limited space available, yet easily accessible and all parts subject to wear easy to renew, and of a mininum weight for a maximum output. They must be capable of running in either direction with fixed brush position, and must operate sparklessly and without undue heating with a very wide range of load. Frequent stopping and starting produce overloads of several times the normal output. It is necessary that they shall be entirely enclosed as a protection against dirt, and they are therefore difficult to cool. They must be able to work all day without attention, and in all conditions of weather, and withstand the very severe mechanical stresses imposed upon them. The insulation must be very good, the working pressure being between 500 to 600 volts. The motors are described in Section VII., page 505.

In deciding upon the type and make of motor for any particular conditions, there are several points to observe. The speed of the motor armature and gear ratio must be properly chosen with regard to the maximum gradient, acceleration, and speed of car on the level, to produce the tractive effort required. The regulation of speed should be simple, reliable and perfectly adapted to all grades and curves of the track.

Between every two stops the car goes through a cycle of operations as follows:

(1) The car is accelerated from rest up to a certain speed.

(2) This speed is maintained for a length of time, with perhaps a reduction of speed on ascending a gradient, or the power cut off in descending.

(3) The power is cut off and the car is allowed to drift, the speed gradually decreasing.

(4) The brakes are applied and the car brought to rest.

(5) A period of rest, after which the cycle is repeated.

Horse-power required.—One of the most important considerations is that of the power to propel a car. The first figure necessary is the power required on the level, which is expressed in horse-power by tractive effort multiplied by the number of feet traversed per minute, and divided by 33,000. The tractive effort is equal to the tractive resistance when the speed is uniform. This may be expressed as follows:

Let W = Weight of car load in tons,
D = Distance travelled in feet,
t = Time in minutes,
S = Speed in miles per hour,
F = Tractive resistance in lbs. per ton weight (for tramway cars about 30 lbs. per ton),

$$\text{then H.P.} = \frac{F \times W \times D}{33{,}000 \times t}$$

One mile per hour = 88 feet per minute,

$$\therefore S = \frac{D}{t \times 88} \text{ and H.P.} = \frac{88}{33{,}000} \times F \times W \times S$$
$$= {\cdot}00267\ F\ W\ S.$$

Gradients.—The inclination of a gradient is generally expressed as distance travelled in feet for a vertical rise of 1 foot, although it is sometimes expressed as a percentage. Thus a gradient of 1 in 30 means that for every 30 feet travelled the car rises 1 foot vertically; this would otherwise be called a 3·3 per cent. gradient.

In finding the power to propel a car up a gradient at a uniform speed, we must first find the power necessary for that speed on the level, and then to this must be added the power to overcome the force of gravity. This may be expressed as follows:

Let x = per cent. of gradient.

$$\left.\begin{array}{l}\text{then H.P. due}\\ \text{to gradient}\end{array}\right\} = \frac{88}{33{,}000} S \times W \times 2{,}240 \frac{x}{100}$$
$$= {\cdot}00267 \times S \times W \times 22{\cdot}4\ x.$$
$$\text{Total H.P.} = {\cdot}00267 \times S \times W\,(F + 22{\cdot}4\ x).$$

Acceleration.—In starting up a car from rest, or in increasing speed, power is used in storing energy in the moving mass of the car and its load, as follows:—

Let K = Energy in foot-pounds,
m = Mass of car,
v = Final velocity in feet per second.
t = time in minutes required to accelerate,

$$\text{then } K = \tfrac{1}{2} m v^2$$
$$\text{Rate of doing work} = \frac{K}{t} = \frac{\frac{1}{2} m v^2}{t}$$
$$\text{H.P. for constant acceleration} = \frac{\frac{1}{2}\,\frac{W \times 2{,}240}{32{\cdot}2} \times \frac{v^2}{t}}{33{,}000}$$

A car weighing with load 10 tons running under the following conditions:

(1) Starting from rest and reaching a speed of 10 miles per hour in three-quarters of a minute on the level;

(2) The same as (1), but on an 8 per cent. grade.

(3) Uniform speed of 10 miles per hour on an 8 per cent. grade;

(4) Same as (3) but on the level.

In (1) the maximum horse-power depends upon the speed; the highest speed is 10 miles per hour.

Horse-power necessary to overcome tractive resistance = ·00267 × 30 × 10 × 10 = 8.

$$\left.\begin{array}{l}\text{H.P. for ac-}\\ \text{celeration}\end{array}\right\} = \frac{\frac{1}{2} \times \frac{10 \times 2{,}240}{32{\cdot}2} \times \frac{\left(\frac{880}{60}\right)^2}{{\cdot}75}}{33{,}000} = 3.$$

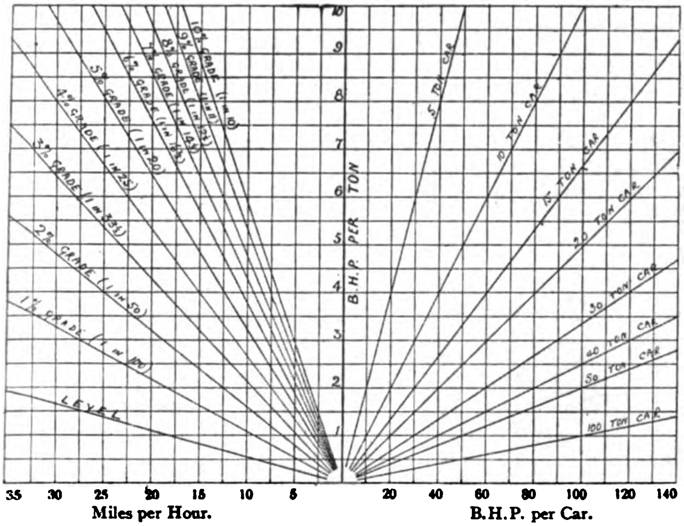
∴ Total power for (1) = 8 + 3 = 11 H.P.

(2) Power required to propel car up a gradient of 8 per cent. = ·00267 × 10 × 10 (30 + 22·4 × 8) = 56 H.P.

Power required for acceleration = 3 H.P. from above.

∴ Total power = 56 + 3 = 59 H.P.

(3) Power to maintain uniform speed of 10 miles per hour on a grade of 8 per cent. = ·00267 × 10 × 10 (30 × 22·4 × 8) = 56 H.P.



Brake Horse Power.	Amperes required per Car at 500 volts, with a motor efficiency of :—	
	60 %	70 %
20	49·8	42·6
40	99·6	85
60	149	128
80	199	170
100	249	213
120	298	256
140	348	298
B.H.P	80 %	90 %
20	37·3	33·2
40	74·6	66·4
60	112	99·6
80	149	132·8
100	187	166
120	224	199
140	261	232

FIG. 751.—CURVES SHOWING APPROXIMATE H.P. REQUIRED FOR CARS UNDER GIVEN CONDITIONS OF SPEED, GRADIENT AND WEIGHT.

(Reproduced from the B.I. Handbook by permission of the publishers.)

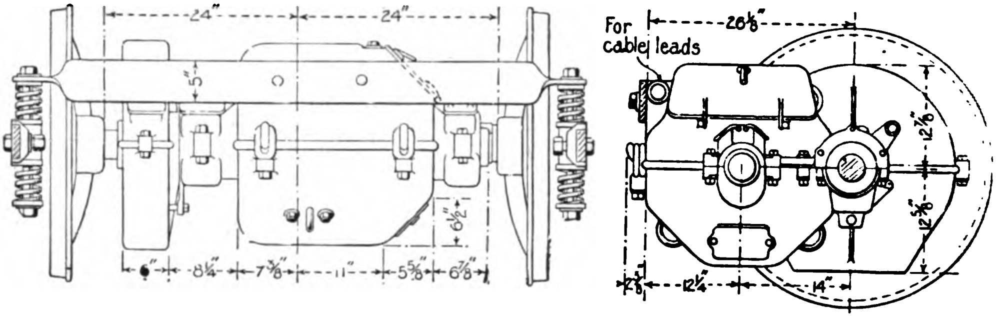
(4) Power to maintain uniform speed of 10 miles per hour on the level = ·00267 × 30 × 10 × 10 = 8 H.P.

Fig. 751 gives the power required per ton for various gradients at different speeds. These are the figures used for street tramway work generally.

At present the various makers all build their machines on very similar lines, the conditions under which the motors work in various countries being very similar. Excepting in a few special cases, motors are series wound, have four poles, and a two circuit wave-wound armature with two brushes, and are made for working in pairs on series parallel control. At starting the motors are coupled in series, as described later under "Controllers."

The series-wound motor gives a large torque at starting and with slow speeds; the strong magnetic field due to the series coils produces this, and also helps towards sparkless commutation on overloads. Carbon brushes are used and are held radially against the commutator; they should bear with slightly more pressure on the commutator than is usual with generators and stationary motors.

The armature is drum wound with former-wound coils, the wire having asbestos covering, as well as cotton. The frame of the motor is of cast steel and entirely encloses the whole of the motor; it is made in two halves, as in Fig. 459, page 507, which shows a Dick, Kerr tram-car motor open, showing the two upper poles, the brush gear and armature. The poles are laminated, and held in place by bolts, with nuts on the outside of the case. The field coils are heavily insulated and waterproofed, the wire generally being asbestos and cotton covered, as on the armature. The coils are held in place by the projecting pole tips.



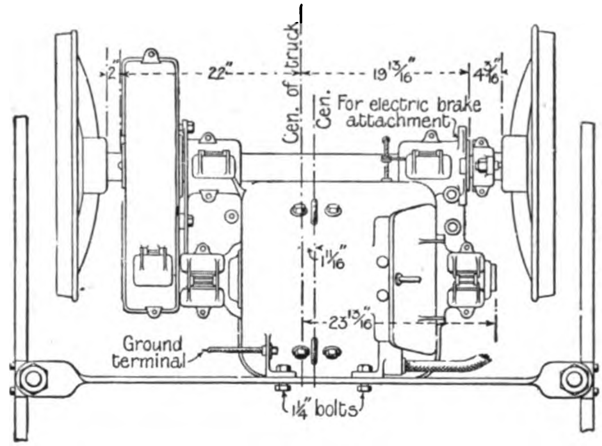


FIG. 752.—MOTOR SUSPENSION SHOWING SPRINGS (DICK, KERR AND CO.).

Fig. 752 shows the method of suspending a motor on the truck. One side of the motor is supported from the axle by means of special bearings springing from the motor frame. A steel cross bar is bolted to two lugs on the opposite side of the motor, and this is supported by springs from the side frames of the truck.

Rating.—The capacity of a motor is limited by the temperature rise and sparking limit. In the early days of electric traction, the rating of motors was not very definite, but the method recommended by the American Institution of Electrical Engineers for determining the rating of traction motors, now universally adopted, is as follows. The rating of a motor is that horse power which it will give out continuously for one hour with a rise of temperature, measured with a thermometer, nowhere exceeding 75° Cent., with an atmospheric temperature of not more than 25° Cent. (*see* page 650).

When stationary the ventilation and cooling are less than when on the road, and to allow for this the commutator cover is left off. This has been found to give conditions about equal to those met when running on the road.

Owing to the constantly varying load, both the heating and sparking limits may be easily reached (the sparking limit at starting and accelerating, though only for a few seconds), while it is possible for the heating limit to be reached while climbing a long grade, although the motor is operating far below its sparking limit. It must be remembered that the generation of heat is not continuous (there being periods of rest and coasting), while radiation is always going on.

Fig. 753 shows the characteristic curves of a 30 horse-power series-wound traction motor, with a gear ratio of 4·85 to 1, with 30 in. diameter car wheel. From this it will be seen that as the tractive effort or drawbar pull increases the speed rapidly falls, and at the same time the current increases. The tractive effort from this curve is approximately proportional to the current raised to the 1·3 power, and the speed varies inversely as some power of the current. Since a shunt motor tends to run at constant speed if the excitation is unaltered, its demand for current at starting and when climbing a gradient is greater than that of a series motor. The acceleration is greater in this case. The use of such motors would cause larger load fluctuations at the power station, and they would require to be larger and heavier than series motors, as well as necessitating an increase in the area of the feeder cables and trolley wires.

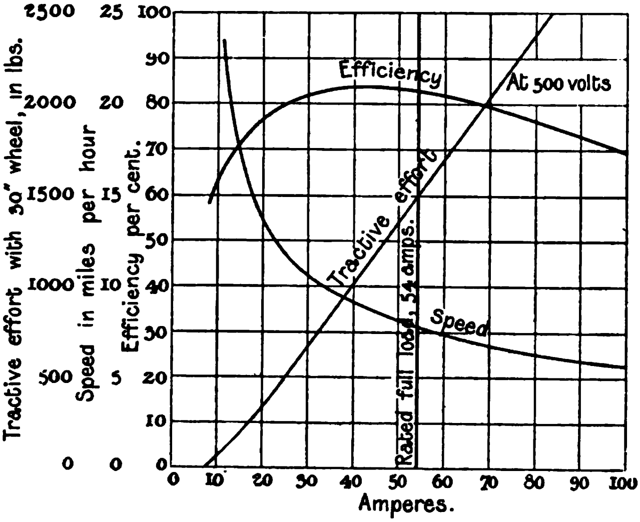


FIG. 753.—TRACTION MOTOR CHARACTERISTIC

CONTROLLERS.

Series Parallel Control.—Cars are now generally equipped with two motors, a simple resistance control as indicated on page 716 being found insufficient. The speed of a motor under given conditions of load is very nearly proportional to the impressed *voltage*, while the torque as shown in Fig. 753 is proportional to the *current* raised to the 1·3 power. The maximum torque is required for starting and accelerating, that is at a time when the speed is low and there is little or no back E.M.F. If the motors are connected in series, the torque produced will be double that from the motors in parallel with the same line current, the voltage being double. When the maximum speed with the motors in series is reached, each is operating on half the line voltage, so they are then switched in parallel, but with resistance between them and the line, and then this resistance is gradually cut out. From this it will be seen that a series-parallel control economises current, and the demand on the power station at starting is halved.

The successive functions of a modern controller are as follows:

(1) To connect both motors in series with one another and to the line through the whole of the regulating resistance;

(2) To cut out the resistance in steps until the motors, still in series, are directly connected to the line;

(3) To connect the motors in parallel with one another and to the line through the resistance;

(4) To cut out the resistance in steps until the motors, now in parallel, are directly connected to the line;

(5) To disconnect the motors from the

line and connect them at both terminals to the resistance. They then act as generators driven by the car, which they therefore brake;

(6) To reverse the armature connections, and so reverse the direction of rotation of the motors.

Fig. 754 shows a modern controller with the front cover removed, showing the power and reversing barrels. These carry a number of metal segments, a row of spring contact fingers being placed parallel to the barrel, so that they may make contact with the segments on the barrel in due sequence as the barrels are rotated. Some controllers are provided with an electromagnetic blow out, the main current passing through a coil of a few turns, which is placed near the bottom of the controller. An iron plate with flanges between the contact fingers runs the whole length of the barrel, and when brought into contact with the iron core, the flanges act as pole pieces. This plate is arranged so that it can be turned back on hinges to allow of inspection of the fingers. The flux between the pole pieces prevents serious arcing at the contacts. Another method is to break contact at several points at the same instant, and this method is used in the controller shown in Fig. 754.

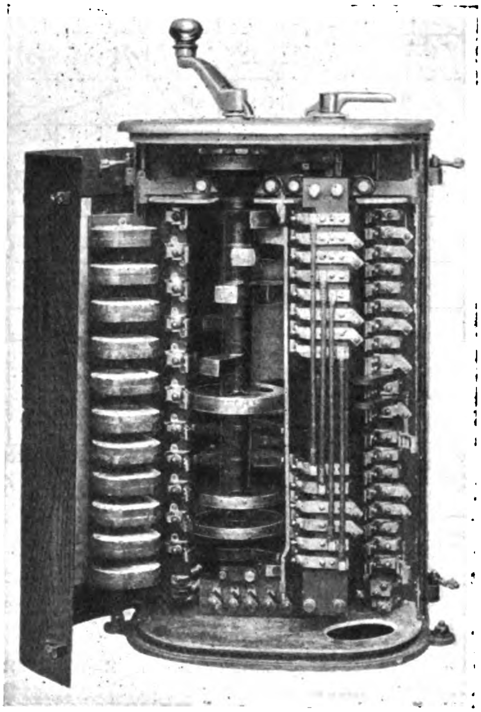


FIG. 754.—INTERIOR OF BRUSH COMPANY'S CAR CONTROLLER.

Controllers are operated by two handles which are removable; the reversing handle is a small one and is used for carrying out operation No. 6, enumerated above. The larger power handle effects the first five changes, and is in constant use. The handles are mechanically interlocked: the power handle cannot be moved unless the reversing handle is in either the forward or reverse position; the reversing handle cannot be moved unless the power handle is in the off position. Neither handle can be removed from the controller unless in the off position.

Controllers are usually provided with a switch for permanently cutting out either motor in the event of failure. The switch is generally placed at the bottom of the controller.

Each car is equipped with two identical controllers, one at each end of the car. To ensure that only one controller can be operated at a time, each car is supplied with only one pair of handles.

Fig. 755 shows a diagram of the two motors connected in parallel.

Regenerative Control.—The system of regenerative control under Raworth's patents is being tried on several tramways in this country. In this system the motors are compound wound, the series coils being used for emergency purposes only, and normal running performed with the motors as plain shunt machines. When running

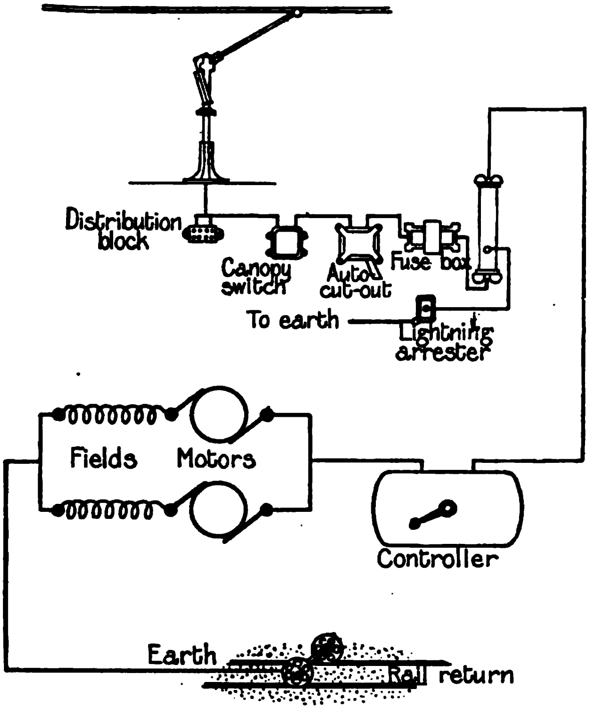


FIG. 755.—DIAGRAM OF TRAM-CAR CIRCUITS.

on a down grade and under all ordinary conditions, brakes are not used; instead, the field excitation is raised so that the motor voltage rises above that of the line. The motors then act as generators, braking the car, and restoring power to the line. On all down grades the motors in this way automatically control the speed without waste of energy, as it is impossible for them to run faster than a certain rate. The system is at its best when the district served is of a hilly nature.

The saving at Devonport is found to be about 30 per cent., or of the order of ·5 B.O.T. units per car mile.

BRAKES.

The first electric cars were fitted with a shoe worked by hand as on the old horse cars. This is totally inadequate, as the speed of the electric car is more than double that of the horse-drawn car, and the car is much heavier. Also there is always a certain amount of slack to be taken up by the hand wheel before the shoes come in contact with the wheel, rendering the brake not of much use in case of an emergency, as the time required to apply it is too long. Other braking devices are added, but the hand brake is still a most necessary part of a car's equipment for use in all ordinary stops. The cast-iron brake shoes are carried on cross members, inequalities in wear of the four shoes being compensated for as shown in Fig. 756. The brakes can be applied from either end, and are provided with means of adjustment for taking up wear.

Drivers often apply too much force to the brake handle and so lock the wheels, the

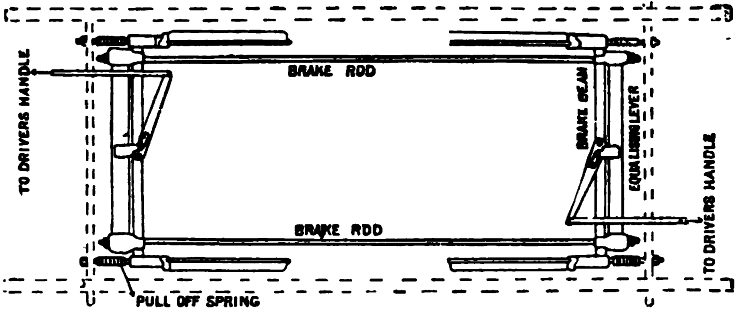


FIG. 756.—BRAKE-RIGGING SHOWING COMPENSATION.

(By permission from Messrs. Wilson and Lydall's "Electrical Traction.")

effect of which is skidding; this enormously reduces the retarding effect, and wears flats on the wheels. If skidding should occur the brake should be released and, when the wheels begin to revolve, be re-applied less forcibly.

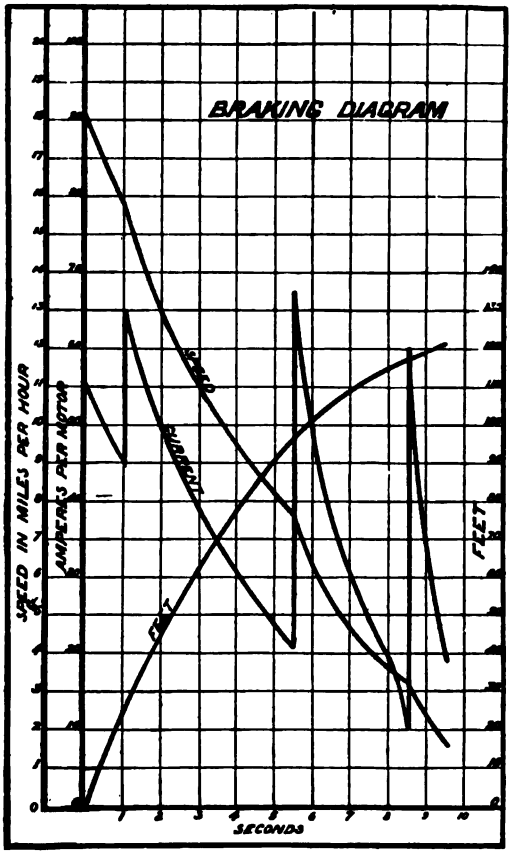


FIG. 757.—BRAKING DIAGRAM.

A supply of dry sand is generally carried upon the car, and by the depression of a foot pedal this may be made to flow upon the tracks and thus help to prevent skidding.

Power Brakes.—When the controller handle is on the brake notches, the motors are connected in parallel and simply short-circuited through a resistance. As the controller handle is moved round the brake notches, the resistance is reduced, until the motors are completely short-circuited.

Fig. 757 shows a braking diagram of a car, with the retarding effect and the current generated on each brake notch.

The amount of braking which is obtained is varied by altering the resistance. It can be raised to such magnitude as to pull the car up in a very short distance. It is impossible for the wheels to become locked, since the action obviously decreases with every reduction in the speed of the wheels.

If the motors are frequently used for retarding, they may be found to heat up seriously, as they will have no rest, even when the car is descending a grade. On the other hand, if the power brake is used reasonably, the extra heating due to it will not do any harm.

As a last resource the motors may be reversed while the car is running in a forward direction. This should only be done when all other means fail, but it should be done quickly, as the only chance of its success lies in its application before the car has attained too great a speed.

Slipper Brakes.—Cars which have to serve very hilly districts are generally equipped with a third brake, known as a slipper brake. This consists of two blocks of wood about 14 in. by 2 in., which are pressed on to the rails, one on each side of the car. This is generally operated by a hand wheel on the platform under the shoe-brake lever. In action this brake reduces the weight on the car wheels, and tends to lift them from the track; a large braking effect being produced without wearing the wheels or causing flats.

Westinghouse Magnetic Brake.—This consists of an electromagnet hung so as to be attracted to the track rails when energised ; it has detachable steel track shoes fixed to each pole, and brake blocks of the ordinary type acting on the wheels are connected to it by a simple mechanism. By means of this arrangement the drag of the track magnet on the rails is transmitted also to the wheel shoes. The track shoes normally run just clear of the rails, being suspended by springs; the magnet is energised by current from the car motors working as generators. Fig. 758 shows the brake as applied to a maximum traction truck.

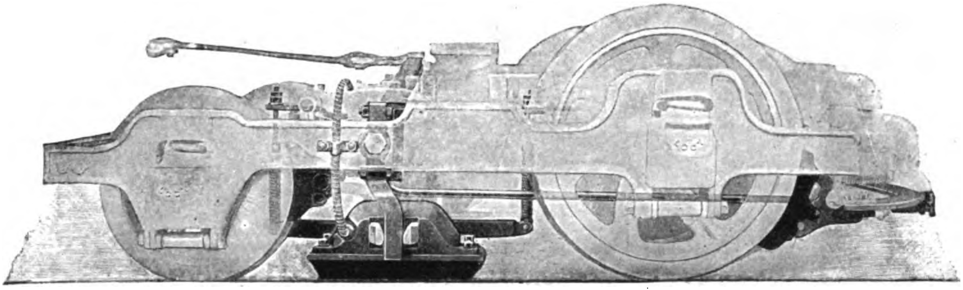


FIG. 758.—WESTINGHOUSE MAGNETIC TRACK BRAKE.

When the brake is applied, the shoes are strongly attracted to and slide along the rails with the following results: (1) Retardation due to the friction between the track shoes and the rails. (2) Braking effect on the wheels. (3) A braking effect on the car axles due to the motors working as generators. (4) An increase in the adhesion of the wheels to the rails, due to the downward pull of the track magnet. The power is regulated by means of the controller, and depends on the number of brake notches on the controller. Any type of controller equipped for rheostatic braking can be used for operating this brake.

This braking effect is very smooth in action ; even when it is necessary to apply the whole power when running at high speed ; there is an entire absence of the jerking which is noticeable with other types of emergency brake. The use of this brake has very little heating effect on the motors as the current used is small.

TRUCKS.

Two general types of truck construction are employed for electric cars.

(1) Single trucks having four wheels with a rigid wheel base ;

(2) Double or bogie trucks having eight wheels.

For cars having an over-all length of about 28 feet a four wheel truck with rigid wheel base is generally employed. For cars of greater length it is found necessary to use double or bogie trucks, so that the cars may easily pass round curves. The even running of a car depends a great deal upon the track, but at the same time the type of truck used has a good deal to do with it.

The distance between the centres of the two axles on a four-wheel truck is called the wheel base. On an ordinary car this seldom exceeds 7 feet, the minimum length being about 5 feet 6 in. Unless the car body is short it will be found impossible to obtain smooth running with a short wheel base, as, even at moderate speeds, serious fore and aft oscillations are set up.

Fig. 759 shows a single four-wheel truck. The side frames should be made of heavy forgings in one piece held together by four transverse bars rather than built up by riveting. The springing is clearly shown in the illustration, and it will be seen that the ends of the long body (compared with the wheel base) are supported by struts at each end. There are springs supporting the car body from the axle boxes, and additional springs for supporting the truck.

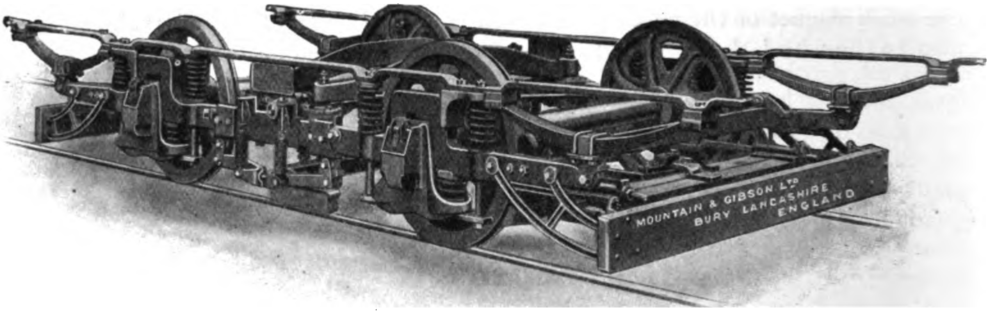


FIG. 759.—FOUR-WHEEL TRAM-CAR TRUCK.

The curves of the track should be made with as large a radius as possible; it is found that with single truck cars a 60 feet radius is about the smallest that they will take comfortably without unduly stressing the truck. With curves of smaller radius, it becomes necessary to use bogie trucks. The trucks are so arranged that they can swivel and follow the track without imposing stresses on the car body. There are several disadvantages in using bogies. As there are usually only two motors per car, the whole of the weight of the car is not available for adhesion. With equal wheels and the car supported at points over the centre of each truck, only 50 per cent. of the weight will

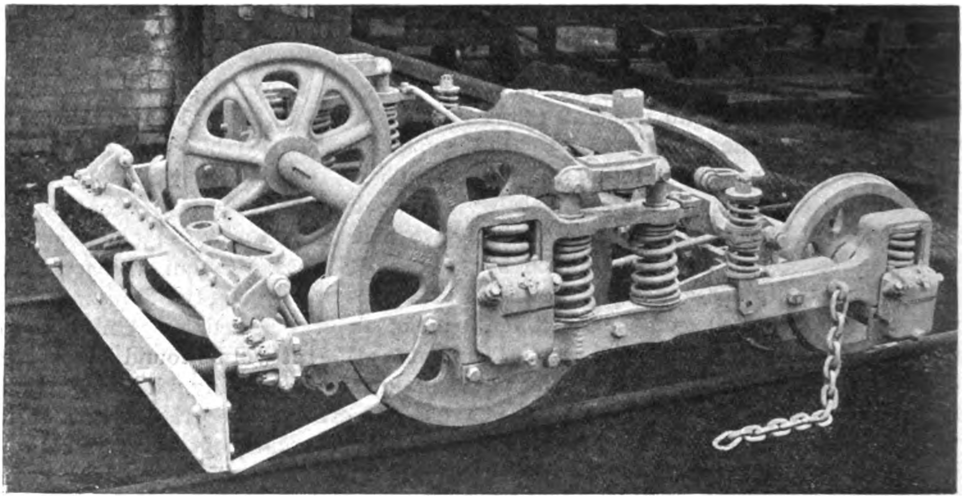


FIG. 760.—BRUSH MAXIMUM-TRACTION TRUCK.

be carried by the driving wheels, and there is a great tendency for them to slip. This can be overcome by using four motors, one on each axle, but this increases the cost and the liability to breakdown.

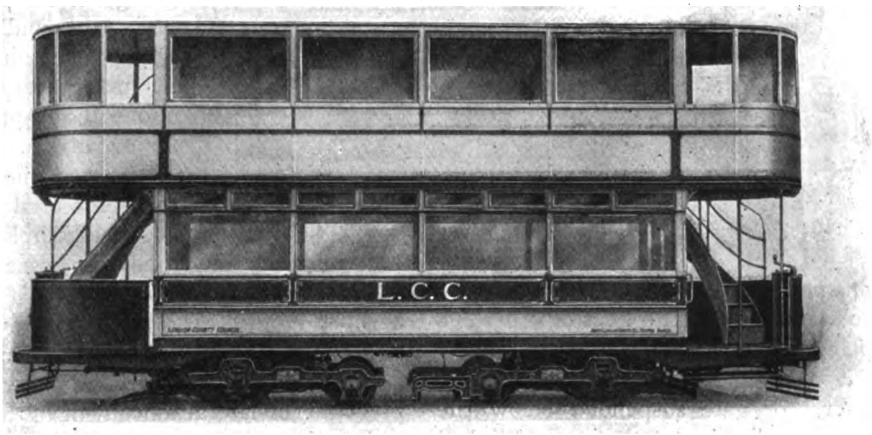


FIG. 761.—L.C.C. CAR UPON MOUNTAIN AND GIBSON TRUCKS.

To enable two motors per car to be used a truck called the "Maximum Traction Truck" is used, as shown in Fig. 760. This has one motor only, which drives the large pair of wheels, the small pair are called "pony wheels." Instead of the weight of the car being carried over the centre of the truck, it is carried from a point nearly over the axle of the driving wheels, the pony wheels simply acting as guides; as they only carry a small part of the weight they are rather given to rising out of the rail when the car is rounding a curve. Attempts have been made to increase the weight on the pony wheels when the bogie swivels, but the results are not very satisfactory.

Fig. 761 shows the latest type of L.C.C. car. The two maximum traction trucks, plough carrier and life guards are well shown.

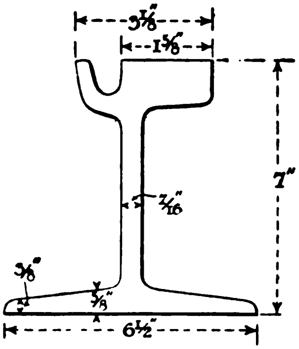


FIG. 762.—SECTION OF L.C.C. TRAM RAILS.

Wheels.—The most satisfactory wheels are those which have wrought-iron centres with steel tyres shrunk on and bolted; the tyres can be renewed and turned when required to take out flats. Cast-iron wheels with chilled rims have been used to a very large extent, but they give trouble by the flanges chipping. Although the cast-iron chilled wheels are cheaper in first cost than wheels with steel rims, they are not so satisfactory and have a shorter life, and are therefore very often dearer.

The axles should be of open hearth steel with a tensile strength of not less than 27 tons per square inch. The wheels are pressed on the axles, no keys or other fixing being used.

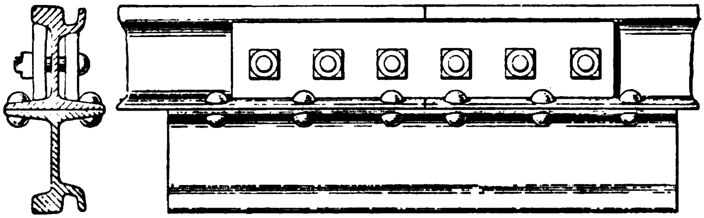


FIG. 763.—RAIL JOINT WITH ANCHOR SOLE PLATE.

Life Guards.—These consist of a "trigger" or gate suspended below the front of the platform of the car and linked to a species of scoop made of light iron framework and carried just before the wheels of the truck. Should the trigger strike any obstruction, the scoop is lowered to receive it.

TRACK.

This is made of steel rail with a wide base, laid on a bed of concrete from 6 in. to 10 in. thick, the gauge being maintained by means of tie rods which are generally about 2 in. by $\frac{3}{8}$ in., spaced 5 feet apart. The road is brought up to the level of the heads of the rails with granite setts or wood-paving blocks.

The usual section of rail used in this country and on the Continent is shown in Fig. 762, which shows a cross section of a 90 pounds per yard rail. The weight of rail used now averages about 90 pounds per yard, and the rails are rolled in lengths of from 30 feet to 60 feet.

The cost of a double track laid complete and the roadway re-paved is about £8,000 to £10,000 per mile.

Joints.—These are usually made with fishplates (Fig. 763). They are of steel, and should have as large a bearing as possible on the flange and head of the rail. Tramway rails being buried in the ground, do not undergo great temperature variations, and consequently the joints may be made very rigid and without provision for expansion.

Fig. 763 shows the rail joint used by the L.C.C. Fishplates are used as usual, and underneath the foot of the rail is riveted a short length of similar rail inverted; this, besides making a very firm joint, forms also an "anchor joint"—that is, it prevents the lateral movement of the rail.

Bonding.—Since with the overhead system the rails are used as return conductors for the current, it is necessary that the resistance shall be kept as low as possible; the resistance of the ordinary joint is very high on account of the rust and dirt on the rails and fishplates. Permanent connection is, therefore, maintained by means of copper connections called "bonds."

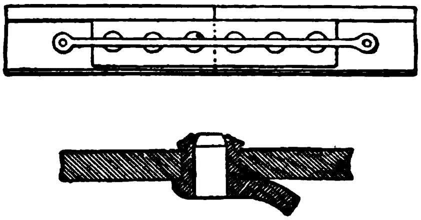


FIG. 764.—"CROWN" BOND.

The requirements of a bond are (1) Permanent contact with the rail and freedom from loosening under vibration. (2) Flexibility. (3) Low prime cost and ease of fixing. There are several types of bonds, some of which have proved successful.

Figs. 764 and 765 show two types of bond in general use. Fig. 764 shows the "Crown" bond, of which there are two types, one solid and the other flexible. The solid bond is made of sufficient length to span the fishplates; the flexible bond is made in two lengths, the long one to span the fishplate, and the short for fixing under the fishplate. The bonds are expanded in the rails by means of a steel pin. The holes in the web of the rails are drilled $\frac{1}{8}$ in. less in diameter than the bond terminal. Just before the bond is inserted in the rail a steel drift is driven through the hole, enlarging it to a little less than the diameter of the bond, this leaves the metal quite clean and bright. The bond is at once driven in, and in being forced in, the copper is scraped clean; the expanding pin is driven in, making a very tight joint. Fig. 765 shows the "Chicago" bond, which is fixed in a very similar manner, except that the pin is driven in from the opposite side to the bond. The cost of bonding a mile of single track with three such bonds per joint is about £200.

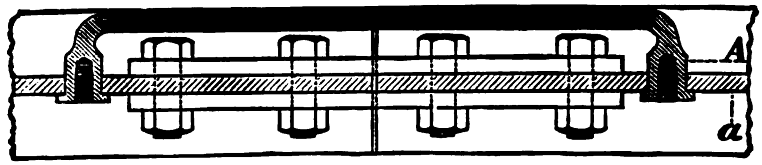


FIG. 765.—"CHICAGO" BOND.

(By permission from Messrs. Wilson and Lydall's "Electrical Traction.")

The "plastic rail" bond, also known as the Edison-Brown bond, is of interest, and deserves notice. It consists of a mercury amalgam, which serves to make conducting connection between the rail and the fishplate, the latter in this case really taking the place of the bond proper. The plastic bond is applied by carefully cleaning two spots on the fishplate, and two corresponding spots on the web of the rails, amalgamating each of these with the special amalgam and water, and then applying the plastic metal to the spots in question. In order to retain this in its proper position, little cork rings are employed, which form with the rail web on the one side and the fishplate on the other, a circular chamber which encloses the plastic metal. With one such bond per joint a mile of single track may be bonded for about £100.

A variant of this type of bond is known as the Edison-Brown solid copper bond, in which a copper bond serves to form the bridge from rail to rail; connection is made between the bond and each rail as described above. Fig. 766 shows a horizontal section through a plastic bond, when the fishplate is used.

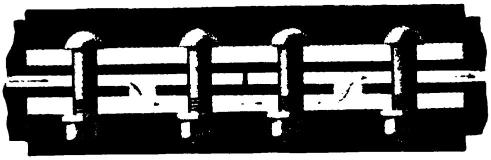


FIG. 766.—PLASTIC RAIL BOND.

Thermit Weld.—This consists of an application of the great heat of combustion of aluminium. If metallic aluminium in a finely powdered state be mixed with an oxide of almost any other metal, the aluminium powder will rob the other oxide of its oxygen and be changed into alumina, that is, aluminium oxide, with the evolution of very great heat, provided only that the reaction can be started. For a long time this operation was a matter of great difficulty, since it was of no use to put the mixture into a crucible and heat it from the outside, for the temperature required was such that the crucible would give way before the desired result could be achieved. Dr. Goldschmidt in 1900 showed that if one of the less stable oxides, such as barium peroxide, were mixed with the metallic aluminium, this mixture could be readily started by means of a large match, and that when started the reaction developed so high a temperature that it served well to start the reaction of the mixture first mentioned. The process now consists essentially of preparing a mixture of iron oxide and aluminium both in a state of fairly fine subdivision, and then firing this mixture by a small amount of a second mixture made of barium peroxide and aluminium. If the materials are placed in a crucible of aluminium or magnesia, the fused mass, which is obtained after firing, consists of two layers, the lower one being molten iron reduced by the aluminium from the iron oxide, on which floats a layer of molten alumina which is lighter than the iron.

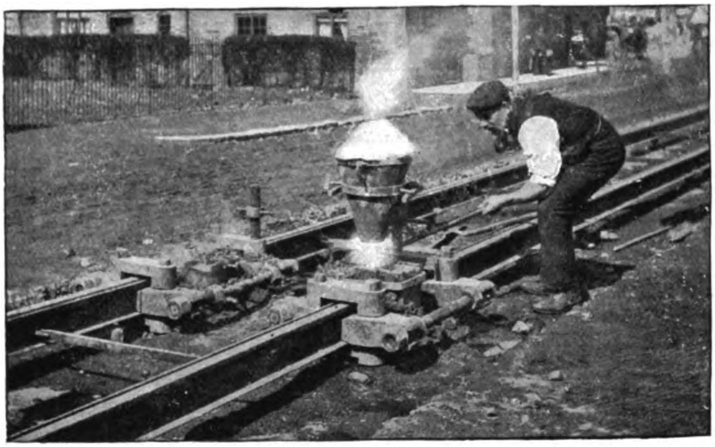


FIG. 767.—THERMIT WELD IN PROGRESS.

When this is applied to the welding of rails, the two ends are cleaned, lined up, and held in fairly close contact by means of screws, while a mould is placed round the joint. A crucible containing the mixture is then ignited, and when the reaction is complete the crucible is tapped at the bottom, the contents allowed to run into the mould, and the ends of the rails forced close together. The iron runs out of the crucible, flows round the web and foot of the rail and, melting them, forms one mass with them. The liquid slag which follows the metal is diverted to the top of the rail, and brings the latter to welding heat. The weld can be made with or without rail clamps.

Fig. 767 shows the crucible just after it has been tapped. The rail clamps and method of supporting the crucible are clearly shown.

The weld thus made not only dispenses with the use of fishplates but also provides good electrical connection between the rails.

CHAPTER II.—TRAMWAY SYSTEMS: THE OVERHEAD SYSTEM.

OVERHEAD—CONDUIT—SURFACE-CONTACT—METHODS OF SUSPENSION OF OVERHEAD WIRES—SIDE-POST—CENTRE-POST—SPAN-WIRE—BRACKET ARMS—INSULATORS—GUARD WIRES—TROLLEY WIRE—SPECIAL POINTS OF CAR EQUIPMENT—TROLLEY ARMS—TROLLEY WHEELS—TROLLEY MASTS—BOWS.

PARTICULAR SYSTEMS.

Overhead.—At present by far the larger number of tramways in the world are worked by this system. It has so far proved itself to be the cheapest, simplest, and most reliable system yet introduced for working street tramways.

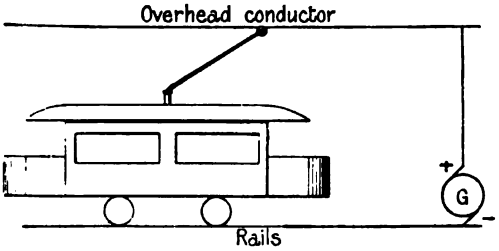


FIG. 768.—TRAMWAY CIRCUIT.

With this system current is conveyed to the moving car by means of a bare conductor called the trolley wire, suspended above the roadway; and returned to the power station by the running rails, as shown in Fig. 768. The usual method of making connection with the trolley wire is by means of a small grooved wheel called the trolley wheel, carried at the end of the arm which projects from the top of the car.

Conduit System.—To get rid of the unsightly network of wires and poles of the overhead system, two others are in use, the conduit and surface contact. In the former system, current is conveyed to and from the cars by means of insulated conductors placed in a conduit under the centre or at the side of the track. A slot is formed the whole length of the track giving access to the conduit, and current is collected from the conductors in the conduit by means of a plough suspended from the underside of the car and passing through the slot.

Surface Contact System.—The disadvantages of the two systems previously mentioned have led engineers to produce this system, which has the disadvantages of neither, *i.e.* the network of wires with the overhead system nor the heavy prime cost with the conduit.

In this system the track is laid with a row of metal studs raised about ½ in. above the surface, and spaced 10 feet to 15 feet apart. These are automatically connected to the mains as the car passes over them and disconnected as the car leaves.

Current is collected from the studs by a long contact bar, or "skate," fixed under the car so that it will rub on the studs as the car travels along. The rails are generally used for the return of the current, as with the overhead system.

For this system to be a success or, indeed, for it to be used at all on a public roadway, studs must only be alive when under a car. This necessitates the use of a separate switch for each stud, to connect it with the mains when the car is over it and to break the circuit just before the car leaves it.

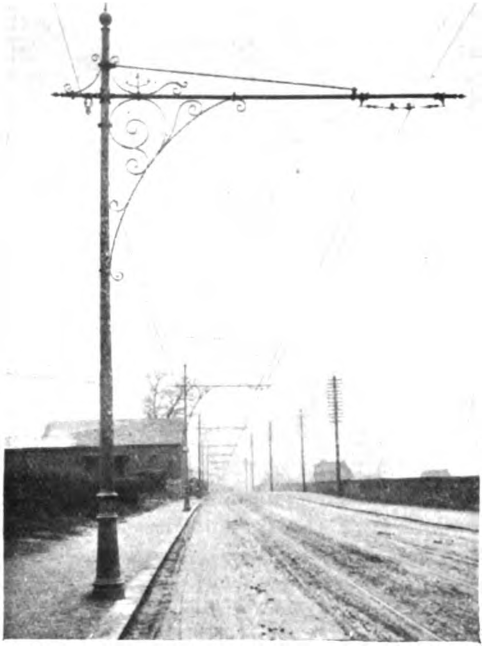


FIG. 769.—BRACKET ARM CONSTRUCTION.

METHOD OF SUSPENSION OF OVERHEAD WIRES.

There are three general methods of supporting the conductors in use :

(1) Side-pole construction,
(2) Centre-pole construction,
(3) Span wires from poles or buildings.

(1) The poles may either be on both sides of the road, each row carrying a separate conductor, or on one side of the road only, the single row carrying two conductors.

(2) With centre-pole construction, the poles are placed between the tracks, which necessitates their being between 5 feet and 6 feet apart, to leave room for a refuge on which each pole is placed. They are best in wide thoroughfares, as the arms do not need to be very long ; they also serve to split up the ordinary traffic.

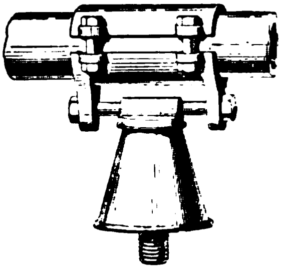


FIG. 770.—BRACKET ARM HANGER.

(3) The conductors are supported by stranded steel span wires attached to poles or buildings. It is preferable where possible to attach the span wires to buildings, this being the cheapest and by far the neatest method. In some cases the span wires must be attached to poles where there are no buildings or where the buildings could not safely stand the strain.

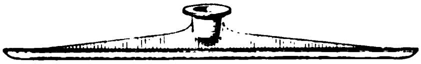


FIG. 771.—TROLLEY EAR.

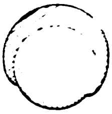


FIG. 772.—SECTION OF EAR.

Centre- and Side-Running Trolleys.—With the centre or under-running trolley the conductor is placed above the centre of the track and a fixed trolley wheel used. With the side-running trolley, the conductor is placed to the side of the track and a swivelling trolley wheel used. On a straight road the side-running trolley is preferable where the conductor is supported on poles, as the length of the bracket is reduced; with side poles under running is not practicable, as the length of the bracket arms would be excessive. On the other hand, with span wires, the conductor can be placed in any position. Side-running is the simplest method at curves, a fewer number of pull-off wires being required, as it is not necessary for the conductor to follow the track so closely as for under-running. For single track working, side-running must be used.

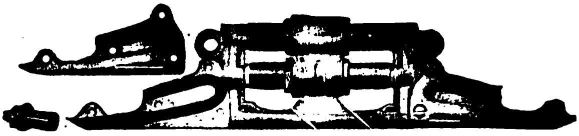


FIG. 773.—AIR-GAP SECTION INSULATOR.

TRAMWAY POLES.

Bracket Arms.—These are usually of thick steel tubing, 2 in. in diameter, securely fixed in a strong cast-iron clamp (which is in two halves) bolted on to the post, as shown in Fig. 769. When the bracket arm does not exceed about 4 feet in length, it is stiff enough to take the weight of the conductor without extra support. The arm in Fig. 769 is shown supported with stays.

Bracket Arm Insulators.—There are several kinds of insulators to carry the "ears," those fixed to the brackets being called "bracket-arm insulators." These consist of a bolt for screwing into the ear, the bolt being embedded in insulating material, which is held in a bronze hood for protection against the weather and mechanical injury. The hood is supported by a second bolt parallel with the bracket arm, on the bottom side of a split sleeve, which is bolted to the bracket arm with insulating material round the arm as shown in Fig. 770.

Ears.—The conductor is supported by means of clips called ears. These are clipped round the conductor as shown in Fig. 772. There are two kinds of ears in use, one solid as shown in Fig. 771, and the other split vertically, with the two halves clamped upon the conductor with screws. The ears are made with a screw boss for attachment to the insulators. The solid ears are soldered to the conductor, the groove being tinned for this purpose, and the thin edges of the ear are hammered over the conductor so as to clip it as well. The ears are gunmetal castings. A common length of ear is about 15 in., but those of 2 feet in length are found to be better.

Section Insulators.—The Board of Trade regulations require that the conductor shall be split up into lengths not exceeding half a mile.

For this purpose "section insulators" are used as shown in Fig. 773. These are provided with clamping terminals for the conductor and for the cables, also with an insulated strip to carry the trolley wheel across the gap between the conductors, which latter should be made so that it may be easily renewed, without taking the strain off the conductors.

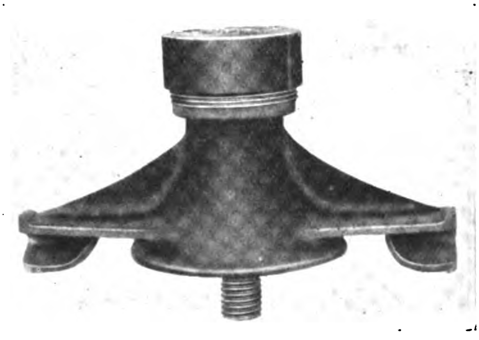


FIG. 774.—THE "PRESCOT" STRAIGHT-LINE HANGER.

Straight-Line and Pull-Off Insulators.—

These are for use with span wire suspension. The insulator is similar to those used on the bracket arm, being provided with two lugs, so that it can be attached to the span wire. This is shown in Fig. 774.

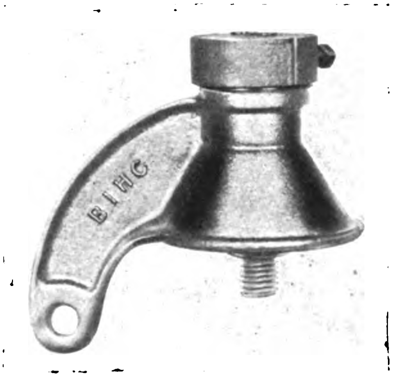


FIG. 775.—SINGLE PULL-OFF INSULATOR.

Pull-off insulators are used on curves, and are called single and double pull-off, according to whether they have one or two lugs, as shown in Figs. 775 and 776.

Turnbuckle Insulators.—These are for adjusting span or pull-off wires, and one is shown in Fig. 777. They consist of an insulated bolt held in a gunmetal cap, and are used on span wires in conjunction with globe insulators. Double insulation is thus obtained.

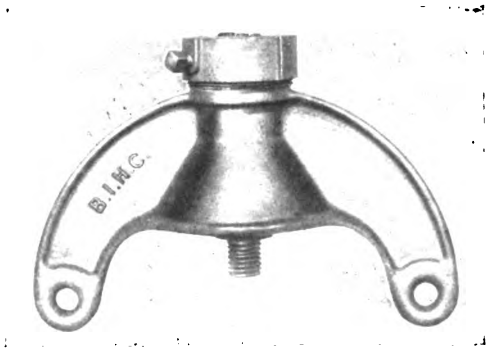


FIG. 776.—DOUBLE PULL-OFF INSULATOR.

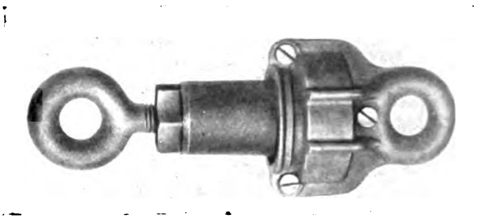


FIG. 777.—"PRESCOT": STRAIN INSULATOR.

Globe Insulators.—These consist of two metal hooks or rings, as shown in Fig. 778, which are interlocked, being kept out of contact by means of a ball of insulating material cast round them. They are so

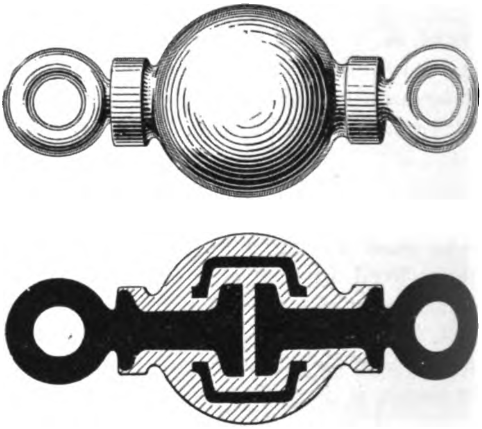


FIG. 778.—GLOBE INSULATOR, AND SECTION.

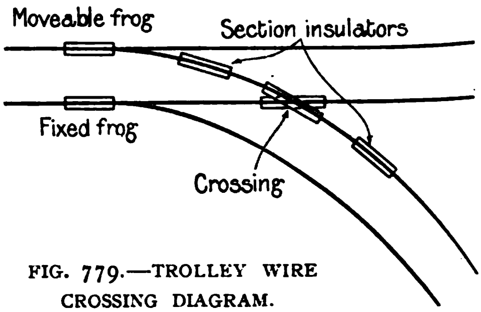


FIG. 779.—TROLLEY WIRE CROSSING DIAGRAM.

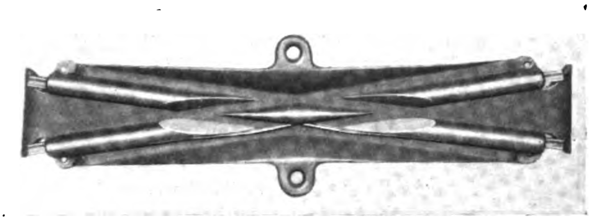


FIG. 780.—PRINGLE TROLLEY CROSSING.

made that in the event of the insulating material failing the line will not fall. Both the turnbuckle and globe insulators will withstand a pull of 4,000 lbs. without damaging the insulating material.

Globe insulators are very often used in bracket arm construction, a short span wire being held by these insulators on the brackets and straight-line insulators being used upon this wire; this gives a more elastic support than with the insulator fixed direct on the arm.

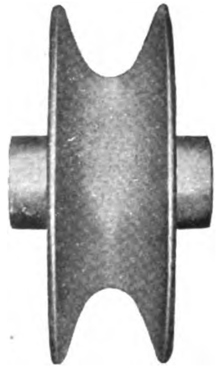


FIG. 781.—"PRESCOT" TROLLEY WHEEL.

Guard Wires.—The Board of Trade regulations require that the conductor shall be protected in such a way that telegraph or telephone wires falling across it, may not hang with live ends in the street, and that at the same time telegraph or telephone apparatus and operators be protected. This protection takes the form of a guard wire or wires suspended above the trolley wires. When used they should in all cases be effectively earthed.

Trolley Wires.—These should be of cold drawn copper, of high conductivity. The usual size is 3/0 S.W.G., *i.e.* ·37 in. diameter; this has a breaking strength of 2·5 tons or a stress of 24 tons to the square inch.

The wire should be in half mile lengths to reach from one section insulator to the next without joints.

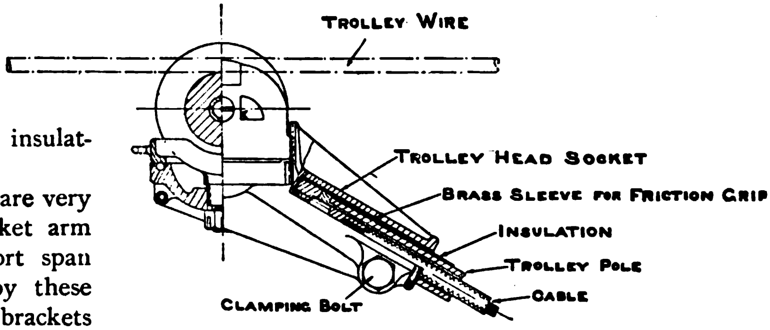


FIG. 782.—SECTION OF SWIVELLING TROLLEY HEAD.

(*By permission from Messrs. Wilson and Lydall's "Electrical Traction."*)

Crossings and Frogs.—Crossings are necessary at junctions on double tracks as shown in Figs. 779 and 780.

Fig. 779 shows an uninsulated crossing in use with section insulators.

Fig. 780 shows a view of an uninsulated crossing. It is necessary that at crossings the conductors be insulated from one another, in case it is necessary to isolate one owing to a fault.

Frogs, or trolley wire switches, are made with both fixed and movable tongues, the movable ones being for use when the car is running against the points. When the tongue is movable it is usual to operate it by means of a wire brought down to an adjacent post, so that the trolley can be directed by the conductor or pointsman.

The overhead equipment for a mile of roadway with two trolley wires costs somewhere between £1,500 and £2,000, or occasionally more.

SPECIAL POINTS OF CAR EQUIPMENT.

Trolley arm.—This is a tapered weldless steel tube, generally about 14 feet long. It is held at the lower end in a casting which can swivel in a vertical and horizontal direction. The arm is held up to the conductor by springs.

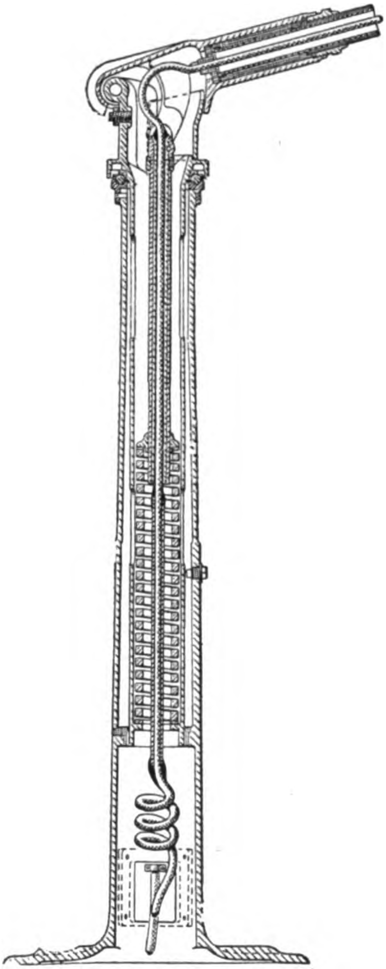


FIG. 783.—TROLLEY MAST: DICK, KERR AND CO.

Trolley Wheel.—Fig. 781 shows the grooved trolley wheel. Some wheels are made with a graphite bushing.

The under-running trolley has a fixed head and a wheel with a **U**-shaped groove.

Swivelling Trolley Head. — Fig. 782 shows a form of swivelling trolley head; it is mounted on a vertical pivot, which is very often supported on balls. This form of trolley head with swivelling base to the arm will follow the conductor perfectly, even if it is 8 feet from the centre of the track.

Trolley Masts.—Fig. 783 shows a trolley mast for double-deck cars. The mast must be very strong to resist the severe stress put upon it in the event of the trolley leaving the conductor. The weak place is at the joint between the mast and the base plate. One of the best forms is a steel tube let into a cast-iron socket in the base plate.

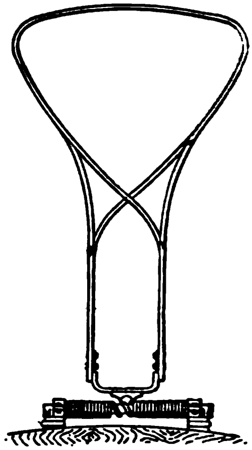


FIG. 784.—BOW COLLECTOR.

Bows.—Fig. 784 shows a bow collector, such as is used largely upon continental tramways, in which, instead of a rolling contact with a wheel, the contact is a sliding one. The contact piece is generally a steel tube, and is sometimes covered with tin. The wear on the conductor is much greater than with the trolley wheel.

The bow has two advantages, it requires no swivelling joints, and works well and easily at curves and points.

CHAPTER III.—CONDUIT AND SURFACE-CONTACT SYSTEMS.

CONDUIT: INTRODUCTION—YOKES—SLOT RAILS—CONDUCTOR RAILS—INSULATORS—PLOUGHS—COST. SURFACE CONTACT: LORAIN SYSTEM—DOLTER SYSTEM—"G. B." SYSTEM.

INTRODUCTION.

THERE are two general types of conduits, viz. centre slot and side slot. Several things are in favour of the adoption of the former; the chief advantage is at points and crossings, as the work with it is far less complicated than with the latter. Usually if the side slot is adopted it is brought to the centre of the track for special work. The objection to the centre slot is the extra amount of metal on the road surface; it is also slightly more expensive, but the difference is so small that it should not carry any weight in deciding which to use.

The construction of the conduits is very similar, whether the slot be at the centre or the side. Cast-iron **U**-shaped yokes are spaced from 3 feet 9 in. to 5 feet apart, for carrying the slot rails and lining up the conduit, which is formed of concrete to the shape of the yokes by wood, or collapsible sheet iron centering on formers; these are withdrawn after the concrete has set.

In Fig. 785 are shown cross sections, with the principal dimensions of conduit construction on L.C.C. tramways. The slot rails are of steel, 60 lbs. per yard **Z** section, 7 in. deep, rolled in 30 feet lengths; at the top there is a lip from which the water drips straight to the bottom of the conduit, instead of creeping round and causing leakage at the insulators. The slot rails and running rails are tied to the yoke, the latter being provided with a lug for the tie bars.

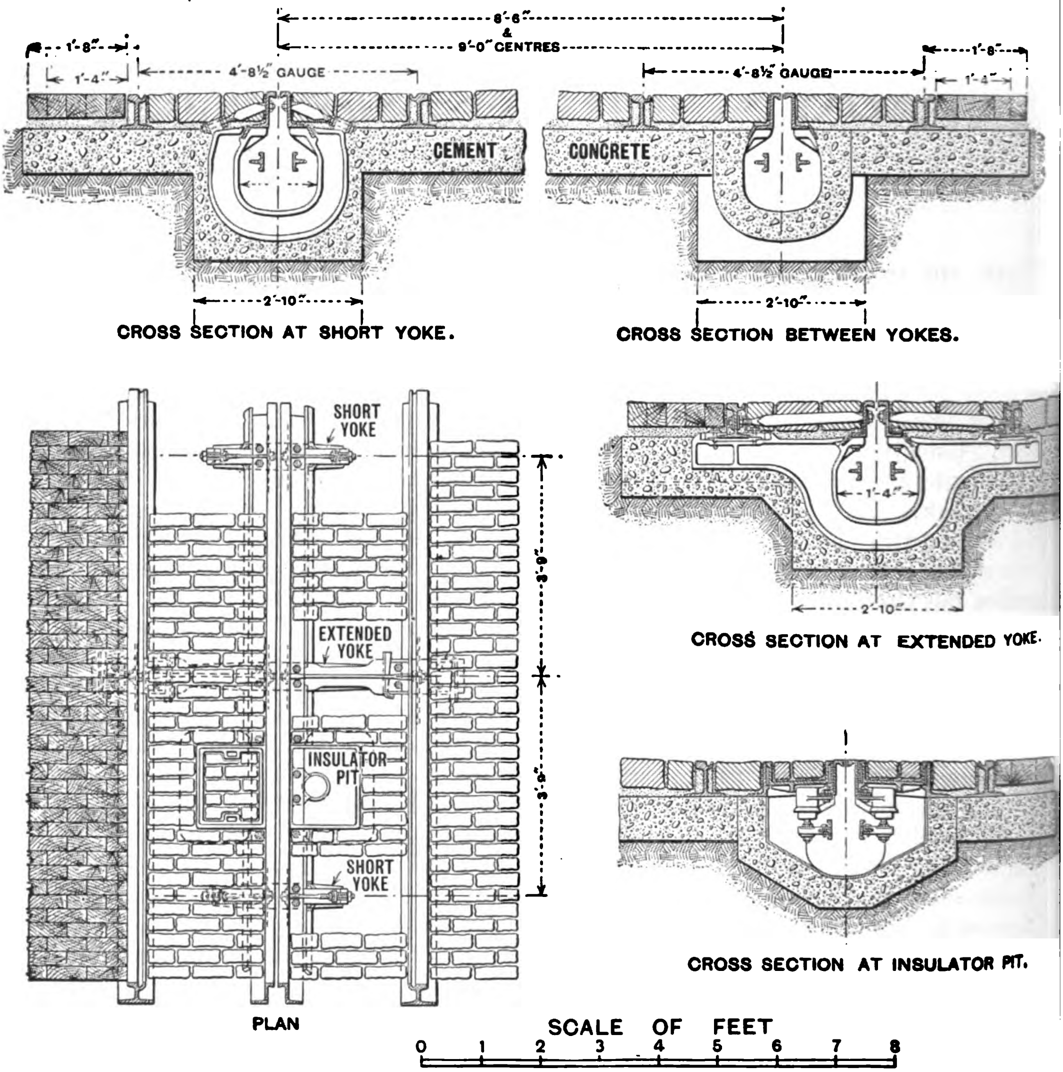
CONDUCTOR RAILS.

The conductor rails are of **T** section, 3½ in. by 2½ in., of very soft steel, weighing 22 lbs. per yard. They are supported on insulators at a depth of 15 in. and 6 in. apart, and are bonded at the joints; but as the running rails do not carry current they are not bonded. The conductor tees are divided into half-mile sections, as in the overhead system, by means of a 2-foot gap, and feeders are connected at these places. At these air gaps the slot is formed by removable plates, and the opening can be used for clearing obstructions from the conduit. Both conductor rails are insulated, and can be made either positive or negative. This is a very useful property of the conduit system, as in the event of a leak taking place on one side of a section at the same time as one on the opposite side of another section, the polarity of one of the half-mile sections can be changed over, so as to bring both leaks on the same side of the system, and thus enable the cars to be kept running until the fault can be rectified. If both leaks occur in the same section, reversing the polarity will, of course, be of no avail.

INSULATORS.

Fig. 785 also shows a section of the insulators mounted in position. These are placed every 15 feet, and consist of a porcelain insulator corrugated both inside and out, the outer corrugations engaging with corresponding ones in a cast-iron cover, the space between being filled in with cement. The inner surface engages with similar corrugations on the insulator bolt, which holds up the conductor rail.

The cast-iron cover is bolted to the bottom flange of the slot rail, the holes in the flange being oval, to allow of horizontal adjustment. There is no vertical adjustment allowed for, as the insulators are


CROSS SECTION AT SHORT YOKE.

CROSS SECTION BETWEEN YOKES.

CROSS SECTION AT EXTENDED YOKE.

CROSS SECTION AT INSULATOR PIT.

PLAN

FIG. 785.—VIEWS OF CONDUIT CONSTRUCTION.

(Reproduced from "Electrical Engineering" by permission of the proprietors.)

assembled to gauge. The clamping bracket at the foot of the insulator bolt is forked, and the web of the conductor rail is secured by a pin put in from above.

Inspection covers, consisting of a cast-iron box paved with setts, are provided at each insulator as seen in Fig. 785.

PLOUGHS.

One of the most important parts of the car's equipment is the apparatus by which the current is brought up to the car from the conductors in the conduit.

The plough must contain two conductors with a potential difference of 500 volts between them, and pass through a slot ¾-in. wide, and at the same time be sufficiently strong mechanically to stand the strain due to travelling at speeds up to twenty miles an hour. It must be able to work under all weather conditions; it is frequently covered with mud and splashed with water from the wheels.

In the type of plough now used in London, the conductors consist of copper tape insulated with mica; the sides of the plough are armoured with steel, which takes the wear at the position where it passes through the slot. The shoes are of cast iron, and are pressed against the conductor tees by means of half elliptic springs placed horizontally. The shoes are connected to the copper strip by means of flexible copper fuses; these are only intended to blow in the case of a short circuit in the plough itself, and will pass 50 per cent. more current than the car circuit breakers are set for. Fig. 786 shows the completed plough.

PLOUGH CARRIER.

The plough is carried on steel runners of **Z** section, which are supported from one of the bogie trucks transversely across the track. The plough is free to travel sideways, and thus can follow any deviations of the conduit from the centre of the track, the carriers being of sufficient length to allow the plough to come right outside the car wheels before it falls off.

COST.

Assuming the cost of the paving and running rails are the same for the conduit system as for the overhead system, there should be added for the conduit per mile of track approximately 105 tons of slot rails, 40 tons of conductor rails, 210 tons of cast-iron, £120 for bolts, etc., £35 for insulators, 1,400 cubic yards excess excavation, 1,200 cubic yards excess concrete, £600 for extra labour for track laying, £400 for sewer connections. Crossings, turnouts and special track work cost 200 per cent. more in general for a conduit than for an ordinary track. These items do not take into account the removal of subsurface obstructions, of which it is quite impossible to foresee the cost; this can often be reduced by varying the depth of the conduit.

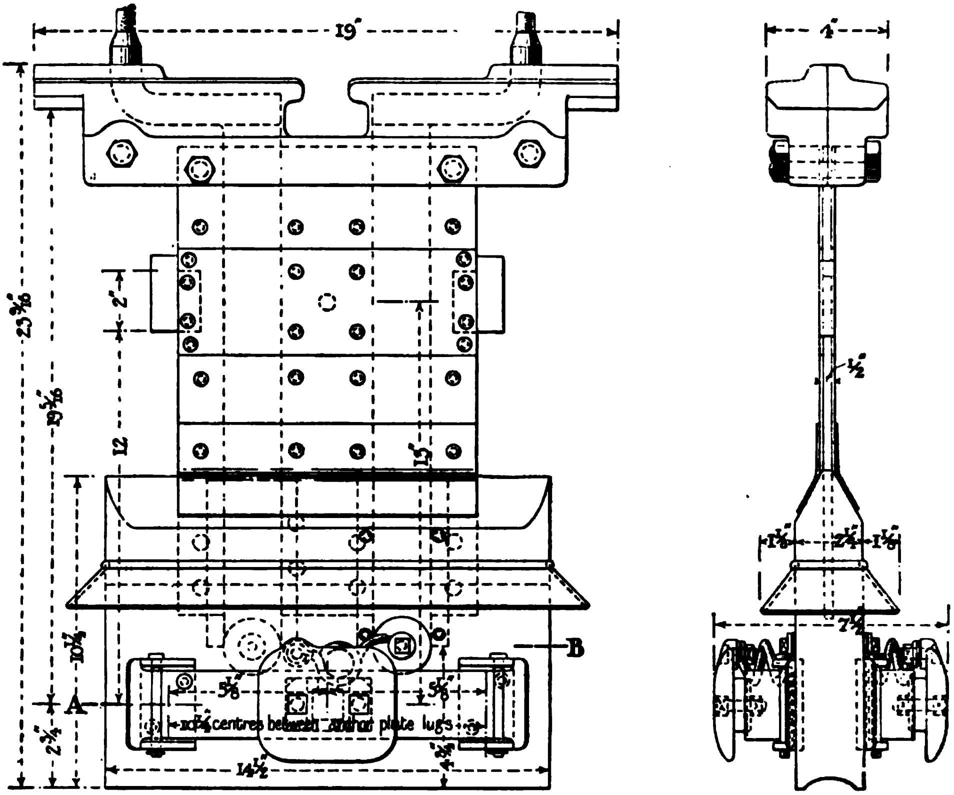
The items (not including the last mentioned) amount to between £5,500 and £6,000, deducting the cost of the overhead construction, conductors, standards, etc.; roughly the conduit would cost from £5,000 to £5,500 more per mile of single track. To this must be added the extra cost of special track work and the removal of underground obstacles.

Estimates of the cost of conduit in the more central districts of London amount to £14,040 per mile of single track. Estimates of the trolley system come out at £7,496 per mile of single track.

COST OF MAINTENANCE.

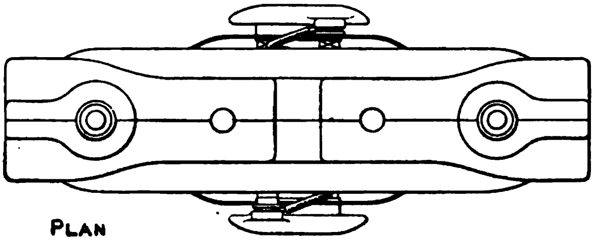
The cost of electrical power is the same as for overhead plus a very small percentage for leakage. The cost of cleaning the conduit is about £100 per mile of single track per annum. The ploughs require overhauling and repairing frequently.

In Brussels the cost of working is found

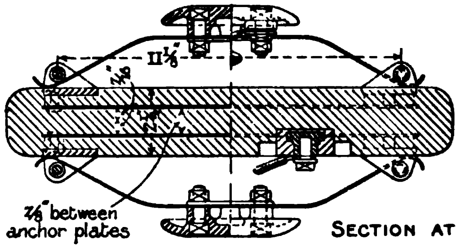


Side Elevation

End Elevation



Plan



Section at A.B.

FIG. 786.—DETAILS OF CONDUIT PLOUGH USED BY LONDON COUNTY COUNCIL.

to be ·2d. per car mile more with the conduit than the overhead. In Paris this increase is found to be about ·5d. per car mile.

SURFACE CONTACT SYSTEMS.

Surface contact systems are many and varied, but three only, which are in use in England, will be described here. The chief merit of this system is that the unsightliness and complication of overhead wires are avoided without involving the great expense of conduit construction. It has generally been adopted where proposals to erect overhead wires have been met with absolute refusal by the local authorities or others, and where the cost of conduit construction would be prohibitive.

The cost of surface contact construction is not greatly in excess of that of the overhead system, but at present it appears to be inferior in point of reliability.

THE LORAIN SYSTEM.

This is the system installed at Wolverhampton. In Fig. 787 is seen a cross section of the stud and box containing the contact mechanism, which consists of two parts, a base of reconstructed granite W W^1, and a metallic cover L L^1 fitting into a recess at the top of the base. The width of this cover is 12¾ in. and its length 6¾ in. The total depth of the box below the rails does not exceed 15 in. and the maximum height above the surface of the paving is ¾ in.

The metallic cover is divided into three parts, the two parts L L^1 being of iron, and the middle of a hard non-magnetic metal. In the base is fitted a brass cylinder E, maintained in position by the ring R, which is screwed on to E and rests on a ledge in W W^1.

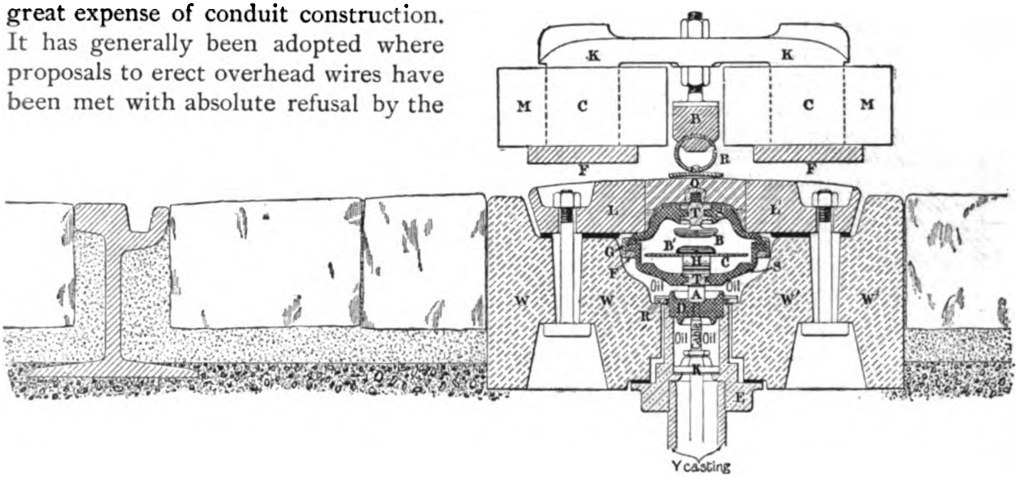


FIG. 787.—SECTION OF LORAIN CONTACT BOX, MAGNET, AND PART OF TRACK.

The cable is laid in pipes running directly under the contact boxes, and at each box a **Y**-shaped casting is fitted into the pipes with its upper end fitting into the lower end of the brass cylinder E. The lead casing of the cable is held by the disc K. At the upper end of the cylinder is an insulated brass bush D, with a tongue A into which the cable is clamped. Above this is the contact chamber which is made in two parts, S S^1, hermetically sealed at G F.

Two brass terminals, T T^1, are moulded into the top and bottom parts of this chamber. The top terminal screws into the non-magnetic part of the cover of the contact box, and the bottom terminal makes contact with the tongue A by means of spring contacts. The actual contact is made between two carbon blocks B B^1 2 in. in diameter.

The top block is fixed to the upper terminal T, and the lower block is connected to the bottom terminal T^1 by means of a flexible strip of copper, which is connected to an iron plate C, fastened under the block B B′ and resting on a ledge in the contact chamber. This plate forms the armature of the electromagnet. The poles of the electromagnet on the car, as shown in Fig. 787, come above L L^1, and the flux passes from one pole through L L^1 to the other pole, attracting the plate C upwards, thus making contact between the blocks B B^1 and O, with which the shoe attached to the car is in contact, alive. The running rails are used as a return for the current. To prevent moisture entering the contact chamber, oil is run in between it and the base of the brass cylinder.

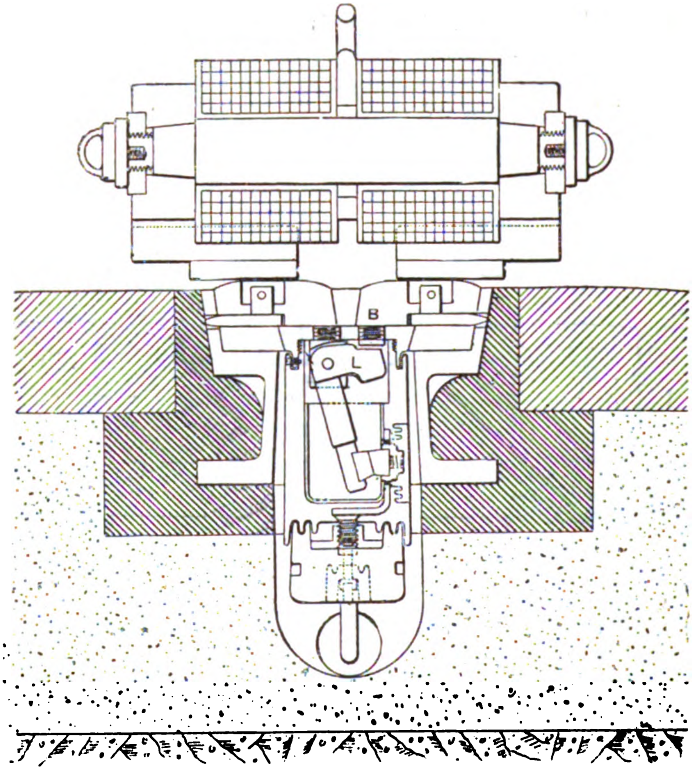


FIG. 788.—DOLTER CONTACT BOX AND COLLECTOR MAGNET.

(By permission from Messrs. Wilson and Lydall's "Electrical Traction.")

Fig. 787 also shows the electromagnet and collecting shoe. The long pole pieces F F of the electromagnets are placed on either side of the centre skate shoe, which is of non-magnetic material and slightly longer than the distance between any two boxes, and is supported by rubber hose R from the wooden bar B. The magnet poles are slightly longer than the collector skate, so that current is never broken in the contact box. An earthing device is carried at each end of the car, which in the event of a stud remaining alive will blow a fuse disconnecting it from the supply.

DOLTER SYSTEM.

This system is working in Paris, Torquay and Hastings. Two iron skates are suspended from the car so that they just touch the studs, which are at intervals of about fifteen feet. These form the upper part of the contact box shown in Fig. 788. The magnetic circuit is completed by the bell crank lever L, the top arm of which is of iron, and is attracted up to the stud B when the skate comes over it, as shown in Fig. 788. On the lower arm is fixed a carbon contact block, arranged so as to make contact with a fixed carbon block connected to the cable. As soon as the skate leaves the stud, the contact piece falls by gravity, being suspended loosely to ensure that it may do so.

A small separate safety skate is placed at each end of the car, and connected to the framework of the car and thus to the wheels and rails; so that in the event of a stud remaining alive, it is short-circuited by this skate, which blows the fuse in the contact box, and disconnects it from the cable. This will not affect the working, as there are always at least two studs under each car.

Current is collected by each skate, and the magnetising current is provided by a small storage battery carried on the car, and kept charged by a shunt from the main motor circuit.

THE "G. B." SYSTEM.

The Griffiths-Bedell system differs considerably from the systems already described. It is remarkable principally for its simplicity and for the fact that the contact studs do not project above the level of the rest of the roadway; this feature is attained by the use of a special collecting device.

The general arrangement of the contact studs and collector is shown in Fig. 789. In an underground duct a bare galvanised steel conductor, upon which are threaded 6 in. lengths of galvanised iron tube, is carried upon insulating reels; the duct is stoneware of oval section, its greatest diameter being about six inches. The steel pins upon which the reels are pivoted, are carried through the duct on one side and all connected together and to the rails by the earthing strip E S, Fig. 790. Any leakage from the conductor due to damp is therefore directly earthed, and cannot get to the contact stud and cause it to be "alive." This overcomes a difficulty experienced with other systems.

The surface contact exposed consists of a piece of cast-iron 10 in. long by 2½ in. wide, to the under side of which is bolted a cast-iron stalk; the lower part of the stalk is divided to form a fork, and lined with brass. Between the prongs of the fork thus formed, an iron switch piece is freely suspended by a steel spring heavily coated with copper. This switch piece is slotted, and its motion limited by a brass pin B P passed through the slot and riveted to the cast-iron fork on each side. The switch piece carries a carbon contact C by means of a copper clip, and the clip is connected by flexible copper leads to the stalk of the stud. At each contact the duct is provided with the branch or extension E seen in Fig. 790, and the recessed granite blocks G are laid in position. The stalk is then inserted and packed with jute at J, and the remaining space is run in with bitumen as seen at B.

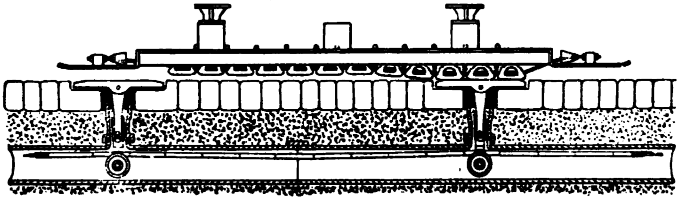


FIG. 789.—"G.B." SURFACE CONTACT SYSTEM.

The Collector.—The collector carried by the car is of a flexible nature, and consists of cast-iron contact pieces C P threaded upon a flexible cable, and suspended by springs between two pieces of metal forming the N pole of an electromagnet; the construction will be easily understood from Fig. 790.

The contact pieces hang normally 2 in.

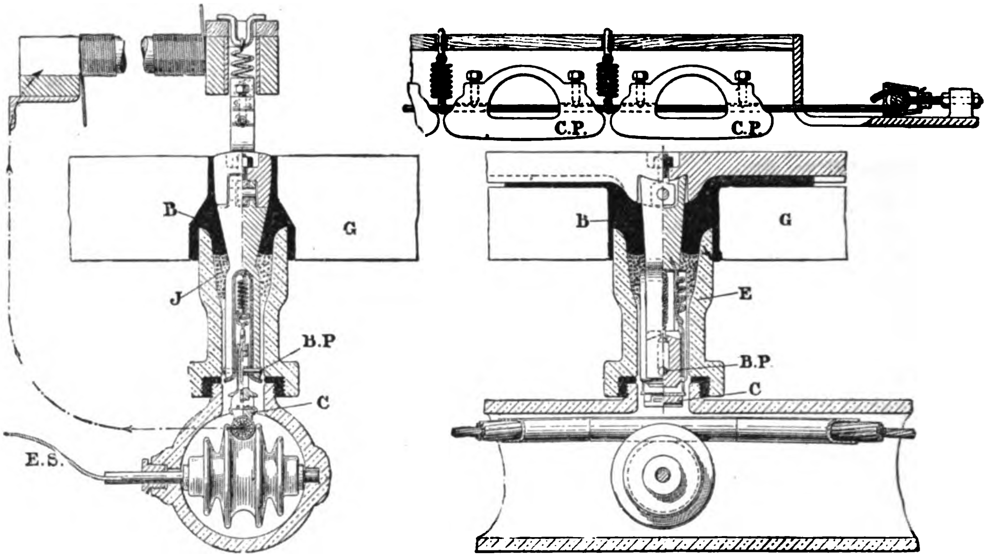


FIG. 790.—SECTIONS OF "G. B." CONTACT SWITCH AND COLLECTOR MAGNET.

above the surface of the road (thus being clear of obstructions such as uneven paving, which causes considerable wear on other forms of skate), but when over a stud are attracted down to it, and the stalk of the stud becoming part of the magnetic circuit, as shown in Fig. 790, the switch piece is, in a similar manner, attracted down to the steel cable, thus completing the electrical connection with the car.

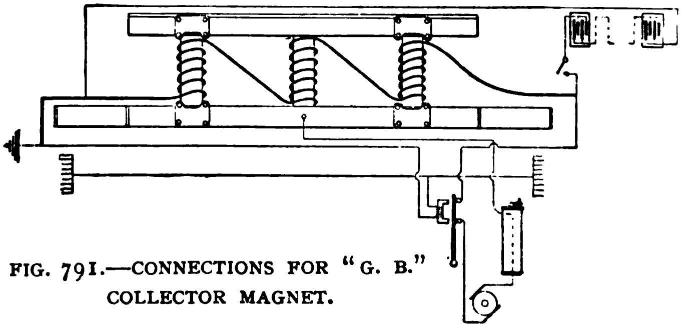


FIG. 791.—CONNECTIONS FOR "G. B." COLLECTOR MAGNET.

Directly the collector magnet has passed from over the stud the switch piece is raised by its spring. A contact arrangement is, however, carried upon the car, which in the case of a stud being left alive, opens a circuit breaker and stops the car.

The excitation current for the magnet is provided by accumulators, which are automatically recharged when the motors are taking current, the magnet being at this time energised by the motor current. The connections are shown in Fig. 791. The energy used by the magnet is 11 amperes at 18 volts, or about 0·025 unit per car mile. The system has been in use at Lincoln for about four years, and has been installed upon a section of the London County Council tramways. Comparative costs for track construction per mile of single track for this last line were given as follows: Conduit, £17,000; G. B., £10,500; Overhead, £9,500.

CHAPTER IV.—RAILWAYS.

INTRODUCTION—RAILWAY MOTORS—SUBURBAN LINES: TRACK EQUIPMENT—MULTIPLE UNIT CONTROL—CITY AND SOUTH LONDON RAILWAY. MAIN LINE RAILWAYS: CATENARY SUSPENSION—NEW YORK, NEW HAVEN AND HARTFORD RAILWAY—SIMPLON TUNNEL INSTALLATION—BOW COLLECTORS.

INTRODUCTION.

WHEN the application of electric motors to purposes of traction is considered, certain advantages at once stand out clearly before the engineer, for the necessary power can be generated economically at a central station and the locomotive has merely to carry the apparatus necessary to convert the required energy from an electrical to a mechanical form, and has not, like the steam locomotive, to carry its source of energy. There are, however, other aspects of the problem, such as the capital expended and depreciation, to be considered, and it is precisely here that there is still a great divergence of opinion as to which side the financial balance will lie. This divergence of opinion is bound to continue until considerably wider experience has been gained, both by engineers and capitalists, in the application of electric traction to lines of considerable length.

While this is the case, it must, however, not be supposed that economy in working is quite undetermined. For tramways, for comparatively short distance lines, and for certain mountain railways, the economy of electric working has been placed beyond all doubt; and the means to be employed, that is to say, the precise details of the electrical equipment, have by dint of experience been reduced pretty much to standard lines.

RAILWAY MOTORS.

Motors for railway use are generally a development of the tramway motor such as has been described (*see* page 506), and the difference is principally in the matter of size. Motors for tramway work are usually of the order of 30 horse power, while for railway work they are often from 150 to 200 horse power, and since the voltage of supply is about the same, more compact design is called for, as the motors have generally to be carried between the wheels of a bogie truck of standard gauge.

When the problem of dealing with ordinary local railway traffic electrically was undertaken, the electric locomotive made its appearance, and the motor design underwent a considerable change. The simplest method of driving the wheels electrically was obviously to build the armature upon the axle, and this method was adopted in many cases, an interesting example being the City and South London Railway, where the armatures are mounted upon the axles of wheels of only 27 in. diameter; the field magnets in this case are of the Edison-Hopkinson bipolar type, and are supported at one end by bearings upon the axle, and suspended at the other by links from the locomotive frame, thus reducing the unspring-borne weight upon the wheels. Another example is afforded by the motors upon the locomotives originally used upon the Central London Railway, the motors in this case being of the four-pole type. The disadvantage of mounting the motor directly upon the axle, is that the dead weight upon the wheels is greatly increased—in the case of the City and South London Railway this is as much as 34 cwt. with motors of only 50 horse power—and this results in excessive wear upon the track.

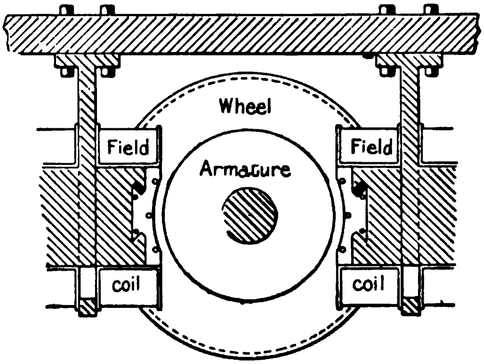


FIG. 792.—ARRANGEMENT OF NEW YORK CENTRAL RAILWAY MOTOR.

To obviate this disadvantage the wheels are sometimes driven by means of a flexible coupling, the motor being mounted upon a sleeve surrounding, but of greater diameter than, the axle, sufficient clearance being allowed to permit of the action of the coupling. Another method of transmitting the power to the wheels is by means of coupling rods, the motors being entirely carried upon the spring-borne frame of the locomotive. This method has been adopted in the case of the Simplon Railway in Switzerland (*see* page 825), the Valtellina Railway in Italy, the London Brighton and South Coast Railway, and other railways. A novel method of direct driving has been adopted by the New York Central Railway, the armatures being in this case mounted directly upon the axles, but the poles of the bipolar field system hung from the spring-borne locomotive frame. The rigid wheel base consists of four pairs of driving wheels, and upon each axle of these an armature is carried. The magnet poles are in a horizontal position between the armatures, and the flux thus goes through all four armatures in series. Fig. 792, shows the general arrangement of one of the inner axles. The gap is of sufficient width to allow the armature to be lowered out of position without touching the pole tips. This wide air-gap necessitates a heavy field construction, but as the weight is necessary for adhesion, this is not a disadvantage.

SUBURBAN LINES.

The Track.—For ordinary suburban work the practice, as we have said, has settled down to fairly standard lines. Continuous current at from 500 to 600 volts is collected by means of a sliding contact called a "shoe" from a "conductor rail" supported upon insulators along the track. From this it is led through a fuse to the controller and motor, and finally returned either to the running rails or an insulated return rail, the latter being the more modern practice. If an insulated return rail is used it is sometimes earthed at some one point, in order that the exact potential of the conductors may be known; but this is not always done. The advantage gained by not earthing the return is that a fault on one conductor makes no difference to the running of the trains. But on the other hand it is a distinct disadvantage to have the potential of the conductors to earth constantly varying.

The relative positions of the conductor rails and track rails is different in almost every instance. Fig. 793 shows sections of the tracks used upon various railways. No doubt special conditions, such as size of tunnel in the case of "tube" railways, influenced the choice of arrangement in some cases, but it appears that some more uniform practice would have been desirable. The arrangement of conductor rails shown at Fig. 793 (4) is perhaps used most extensively. It will be noticed that two conductor rails are used, the negative in the middle and the positive on the most convenient side.

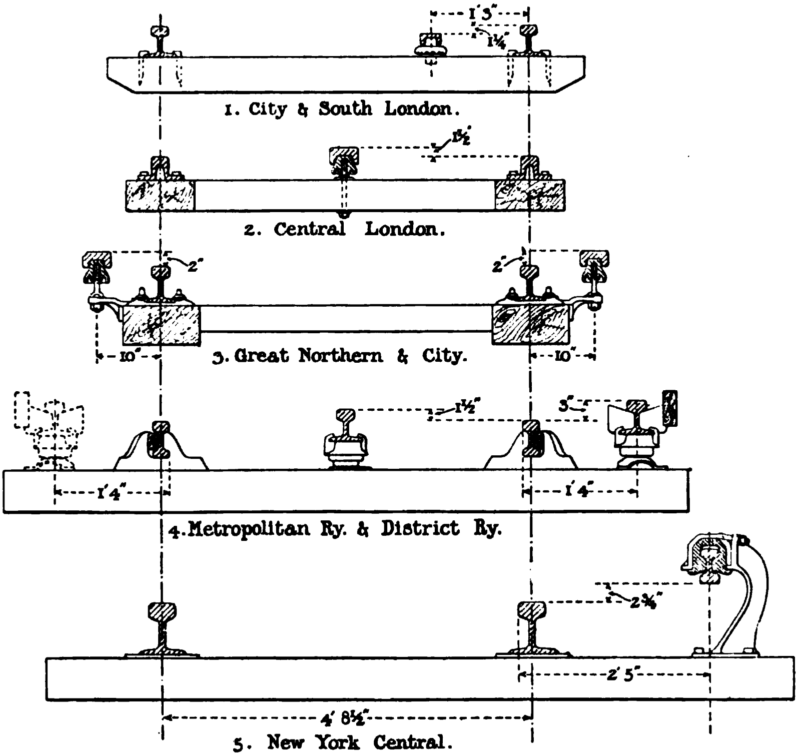


FIG. 793.—SECTIONS OF RAILWAY TRACKS.

Insulators.—The insulators used are generally made of porcelain or stoneware, but glass has also been used. In form they are usually a modification of the telegraph form of insulator, and the conductor rails are carried upon these either directly or by means of metallic clips.

The conductor rails have in some cases been simply fixed to impregnated wood blocks attached to the sleepers, but the leakage in this case is generally excessive, especially in wet weather.

Protection of Conductor Rails.—It is very necessary to protect the conductor rails at places where there is a liability of workmen and others to come into accidental contact with them, and one method of so doing is shown in Fig. 793 (4). It consists of bolting a piece of timber to the rail so that it projects slightly above the level of the rail head, in some cases on both sides of the rail.

The use of such protection in places where the possibility of accident is considerable has been sufficient in England, where the railways are well enclosed and level crossings are few; but in America the use of unprotected conductor rails has been in some cases attended by such a number of fatalities and injuries that electrical operation has been abandoned on this score alone.

Fig. 793 (5) shows a novel form of conductor rail which has been adopted by the New York Central Railway largely because it affords ample protection. From the illustration it will be seen that the conductor rail is of the bull-head type, and is carried from the sleeper, upon a bracket to which it is clamped. The rail is clamped between insulating material and between supports; it is surrounded, with the exception of its lower face, by timber. Current is collected from this rail by means of a shoe exerting pressure in an upward direction. It is claimed for this form of rail that there is less strain upon the insulators, as the pressure of the shoes is against that of gravity, and that the rail is better protected against the accumulation of ice and snow upon the working surface, with the consequent reduction in corrosion and leakage. An overhead conductor rail has also been used, but not to any large extent.

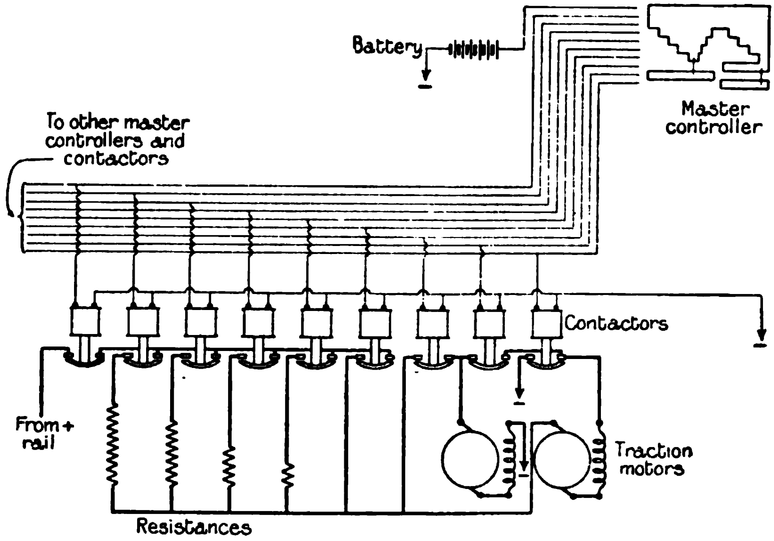


FIG. 794.—DIAGRAM OF MULTIPLE UNIT CONTROL SYSTEM.

MULTIPLE UNIT TRAINS.

Most of the trains upon suburban lines are now made up on what is known as the multiple unit system, the fundamental idea of which is that they shall be composed of a number of "units" each complete in itself, and that they shall be capable of being operated either independently or collectively in either direction.

In practice these units generally consist of two motor cars which may, or may not, have one or more "trailers," that is, cars without motive power, between them. The combination of two such units will, of course, result in the use of intermediate motor cars. The motors used on such trains are generally a development of the ordinary tramway motor, and are geared to the axle in a similar manner.

MULTIPLE UNIT CONTROL.

It will be evident from what we have just said, that the ordinary methods of speed control will have to be modified to meet the conditions of multiple unit working, and many systems have been devised to meet these conditions, but the one outlined below is typical.

The motor cars are each fitted with a complete set of resistances as usual, but the connections to these are not led to a controller, but to electrically operated switches or "contactors" which make the actual connections with the supply; the contactors being in turn controlled by a "master controller" which operates them in the correct sequence. The controller is very similar to that used on an ordinary tramcar, but has only to handle the small current required for the contactors, which is of the order of 2·5 amperes per motor car.

Fig. 794 shows clearly the principle of the system, and by following the connections it will be seen that as the controller handle is revolved the motors are first connected in series, and with all resistance in circuit, the resistance is then decreased until the motors are connected in series across the full voltage. They are then put in parallel with full resistance, and this is finally reduced until the motors are in parallel across the full voltage.

The connections shown are merely those for starting up the motors; but, of course, arrangements for reversing are also necessary. These consist of a reversing handle on each controller and electrically operated reversing switches upon each motor car. In the illustration a battery is shown as a source of current for operating the contactors, but more recent practice is to use current from the conductor rails.

It will be evident from this diagram that if each motor car is equipped with a complete set of contactors and resistances, etc., suitably connected to the controller connections or "train lines," which join all controllers on the train in parallel, all such motor cars may be operated by any one controller. The train lines are therefore carried throughout the train, and it is only necessary to install controllers connected to the train lines, upon those cars from which it is desired to operate the train, to obtain the desired conditions of control.

THE CITY AND SOUTH LONDON RAILWAY.

This railway is interesting in many respects. It was the first deep level or "tube" railway to be constructed, and was also the first instance of the application of electrical power to heavy railway work. The line when opened, in 1890, ran from King William Street, City, to Stockwell, where the generating station is situated, the length being about three and a half miles.

The "up" and "down" lines are in separate tunnels, as has become the practice in tube railways, and the track consists of two running and one conductor rail, as shown in Fig. 793. Locomotives are used. When first opened, current was merely fed into the conductor rails at 500 volts and returned to the power station through the track rails, which were, of course, bonded for that purpose.

About the year 1899 it was decided to extend the line, and accordingly it became necessary to make arrangements for transmitting power to the more distant parts of the line, and to improve the voltage regulation. This had not been good, and fluctuations of the lighting had resulted. A most ingenious system of distribution, which is a species of five-wire system, and which has achieved excellent results in practice, was finally carried out by Mr. McMahon, the engineer to the company.

The Three-Wire System.—The system may in the first place be regarded as a three-wire system in which the conductor rails of the up and down lines form the two outers, and the running rails are all bonded together to form the neutral. Fig. 795 shows a diagram of the system, from which, for the sake of clearness, all lighting and lift connections have been omitted.

It will be noticed that at intervals along the line balancers are connected across the outers; these are of the usual type, and their action is that described on page 750.

The Five-Wire System.—The method of supplying power to the feeding points is shown in the diagram. At Stockwell 500-volt generators, driven either by steam or electricity, are connected between the *outers* and the feeder cables, that is, they are acting as boosters; the total voltage between the feeder cables, and earth thus being 1,000 volts, and 2,000 volts between feeders. At feeding points the current is fed into "reducers" which consist of four armature windings connected in series across the five wires. These windings are carried upon two armature cores which are mechanically coupled and have a commutator at each end. The machines therefore combine the functions of continuous-current transformers and balancers. The current in flowing through the "motor" armature has its voltage reduced from 1,000 volts above earth to 500 volts above earth, the power thus given out being transmitted mechanically to the generator portion of the machine, causing it to feed current at 500 volts above earth into the live rail for the locomotive motors. The feeder circuit current being now reduced to that potential is also fed direct to the conductor rail. It will be seen from the above therefore, that only half the power transmitted from the power station undergoes the change into mechanical form, the other half being fed directly into the live rail in an electrical form, while all the advantages of a 2,000 volt transmission are obtained.

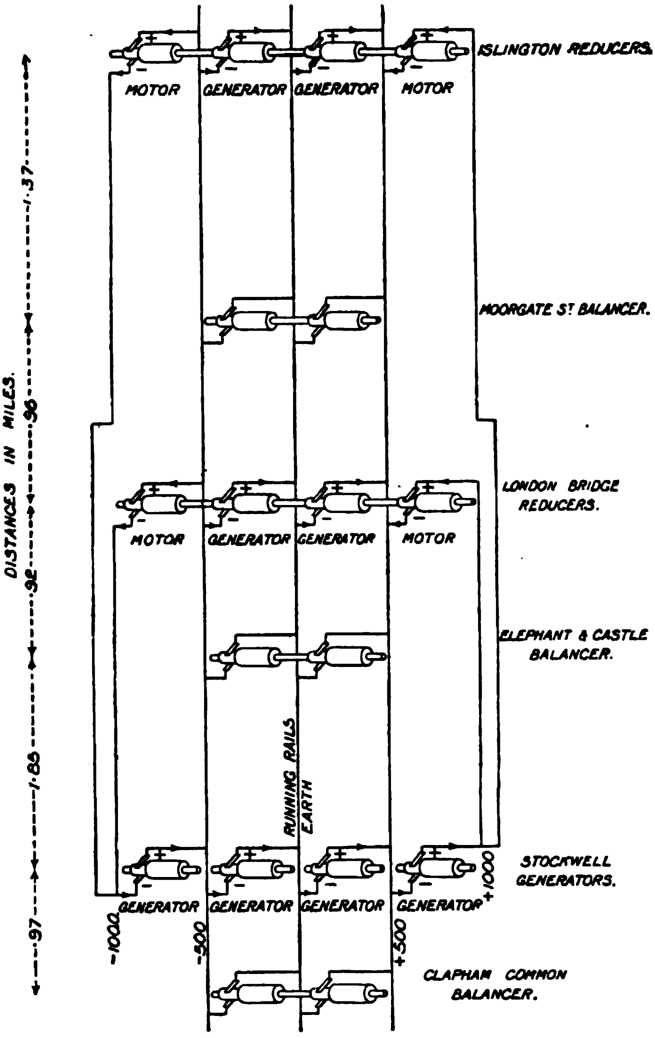


FIG. 795.—DISTRIBUTION SYSTEM OF CITY AND SOUTH LONDON RAILWAY.

The core upon which the "motor" and "generator" windings of the reducers are wound is divided into two parts, one of which is traversed by both sets of winding, and the other and smaller part by the motor winding only. This latter part of the core is provided with a separate series field winding, by means of which any voltage drop in the feeder may be compensated for.

It is possible to supply the motor armatures on both sides of the system from the same generator if desired, and so equalise the load upon the generating station.

In addition to the reducers mentioned above, batteries are installed at the sub-stations and at the generating station. These batteries are installed principally to supply current to the live rail in case of breakdown or heavy load, but they also supply current for the lift and lighting circuits, and for lighting purposes when the generating plant is shut down.

The result of this system has been that unusually good voltage regulation is obtained and the efficiency of transmission is very high, the average net efficiency from the generating station switchboard to the locomotives being 90 per cent.

MAIN LINE RAILWAYS.

The technical difficulties experienced in this connection, have been (*a*) in working at sufficiently high voltages and (*b*) in conveying the current to the trains at main line speeds. The financial difficulty is the expenditure of large capital in equipping line and rolling stock, which expenditure can only be justified by an adequate increased return in earnings.

Dealing first with the difficulties in collecting the current, considerable advantage is apparent in reducing the number of collecting devices wanted. Single-phase working, therefore, holds out an inducement which two- or three-phase working cannot offer. In spite, however, of the enormous strides made by the designers of single-phase motors, commutator difficulties limit the working voltage to a value far below that required for the line voltage, and step-down transformers are, therefore, carried on the train, while three-phase motors may be fed direct at the line voltage. One consideration of great weight is the frequency of stopping and starting. Over a given line, with a given weight of train, with long, uninterrupted runs, a three-phase equipment will offer superior advantages in economy, while if there be many stations involving comparatively frequent stopping and starting, the superior characteristics of the single-phase motor to meet these conditions will lead to its adoption. Fig. 796 gives an interesting comparison of the performance of the three kinds of motor.

We now turn to the financial side of the question. The capital already invested yields only a small, but apparently safe return, which may be put roughly in figures at an average of 3 per cent. on some £1,200,000,000 of capital. Electrical equipment must clearly add heavily to the capital expended, but it is by no means clear that it would add to the earning power in a proportionate degree. Neither does it appear that the substitution of electrical driving for steam locomotives, is likely to effect any decrease in coal or water expended per ton-mile. Economy in upkeep of permanent way was predicted, but does not appear to have been realised; and upon the suburban lines, at any rate, the wear has considerably increased. In regard to increased traffic, multiple unit control permits of much more frequent and accelerated service, without corresponding increase in the running cost, and is thus promising.

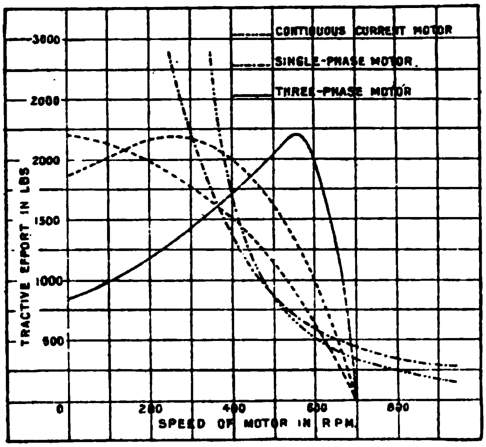


FIG. 796.—COMPARATIVE SPEED AND TRACTIVE EFFORT CURVES OF RAILWAY MOTORS.

(*From the Proceedings of the Institution of Engineer and Shipbuilders in Scotland.*)

For the present we must look abroad for examples of heavy electric traction, where its adoption is to be accounted for either by scarcity of fuel and abundance of water power, the need for better ventilation in the case of long tunnels, or, in some cases in America, by legal requirements, conditions which do not obtain in England.

The methods adopted for heavy railway work differ in several ways from those for suburban work. Higher voltages are desirable for two main reasons, in the first place, to minimise the transmission losses, and in the second place, to render the collection of the power easier. High voltage transmission by alternating-currents to sub-stations at intervals along the line, and conversion at these to low-tension direct current for the locomotives, introduces the difficulty of collecting at high speeds the heavy currents necessary.

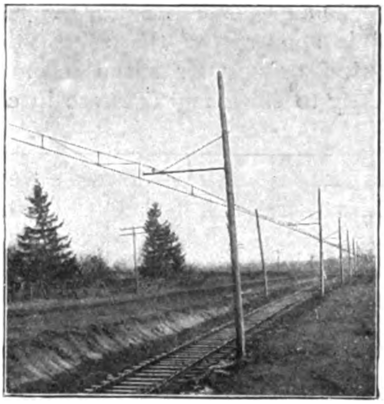


FIG. 797.—SINGLE CATENARY SUSPENSION.

The limit of voltage for which continuous-current motors can be built is about 1,200, but for alternating currents it is higher; further, the adoption of alternating currents allows the use of line pressures higher than the motor voltage, since transformers can be carried on the locomotive.

These high voltages necessitate the use of overhead conductors, since the difficulty of insulating, and the danger attending the use of, conductor rails would be prohibitive.

The high speeds call for improved overhead construction, as serious sparking otherwise occurs, owing to the sag of the wire between the points of support.

CATENARY SUSPENSION.

To overcome this difficulty, catenary suspension, some examples of which (by the Ohio Brass Company) are given in Figs. 797-800, has in most cases been resorted to. Fig. 797 shows a simple catenary construction, from which it will be seen that it consists essentially of two wires, one the catenary suspension wire or "messenger" and the other the trolley proper. The suspension wire is generally of steel, supported upon insulators, and allowed to hang in a catenary; from this the trolley wire is hung at intervals of about 10 ft., by means of short galvanised rods of varying length, so arranged that there is practically no sag of the trolley.

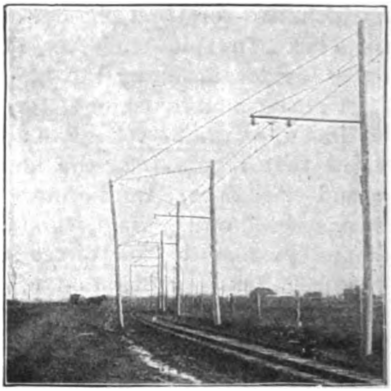


FIG. 798.—CATENARY SUSPENSION AND STEADY BRACKET.

To prevent lateral motion of the trolley, two arrangements, shown in Figs. 798 and 799 are used; in Fig. 798 the lower trolley wire is connected by means of flexible steel wires to insulators placed on each side, while in Fig. 799, one of the trolley-wire supports is rigidly connected to an insulator carried upon the bracket arm.

More elaborate forms of suspension have also been made use of. The Siemens catenary for instance, which has been adopted by the Midland Railway for their line from Lancaster to Morecambe, consists of one main suspension wire, from which another is suspended at intervals, and from this in turn the trolley is suspended at shorter intervals.

THE NEW YORK, NEW HAVEN AND HARTFORD RAILWAY.

We propose to give a short description of some points of interest in connection with the single-phase portion of this line, but before doing so it may be well to point out the chief reasons for adopting this form of traction. In the first place, the company was compelled by Act of Legislature to operate all its lines within a certain distance of New York by some "motive power other than steam, which does not involve combustion in the motors themselves." Some electrical system was therefore imperative, and as the company had to run over lines already equipped on the third-rail continuous-current system, it was necessary that they should adopt either the same system or one which would work in conjunction with it. This limited the choice to continuous current or single-phase alternating current with commutator motors, which could be used as continuous-current motors.

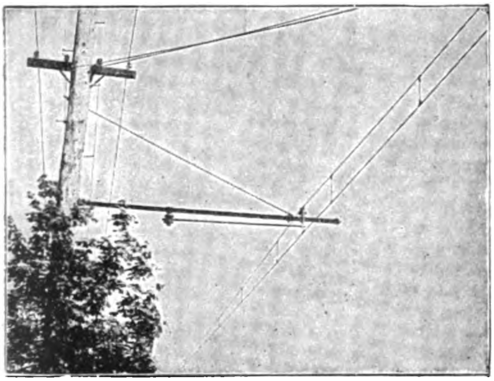


FIG. 799.—STEADY BRACKET.

The experience of the company with continuous-current third-rail working had, however, been unfortunate. They had equipped some 39 miles of their line with this system, but had been compelled, owing to a number of accidents, to revert to steam working. The possibility of generation at about 22,000 volts, and transforming at sub-stations to a lower trolley voltage was next considered, but finally it was decided to transmit power directly to the trolley line at 11,000 volts 25 ∿ from stations which the company already owned, the current being transformed down upon the locomotives to a voltage suitable for the motors, all sub-stations being thus dispensed with.

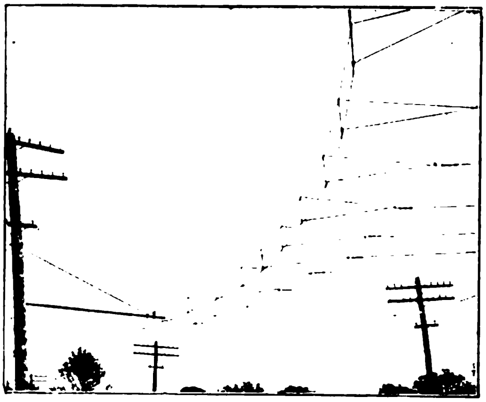


FIG. 800.—CATENARY CURVE.

Three-phase generators are used, one phase being connected to earth and one to the overhead trolley. A conductor is also run along the side of the track from the third phase of the generators, in order that three-phase motors may be used for pumping and similar purposes.

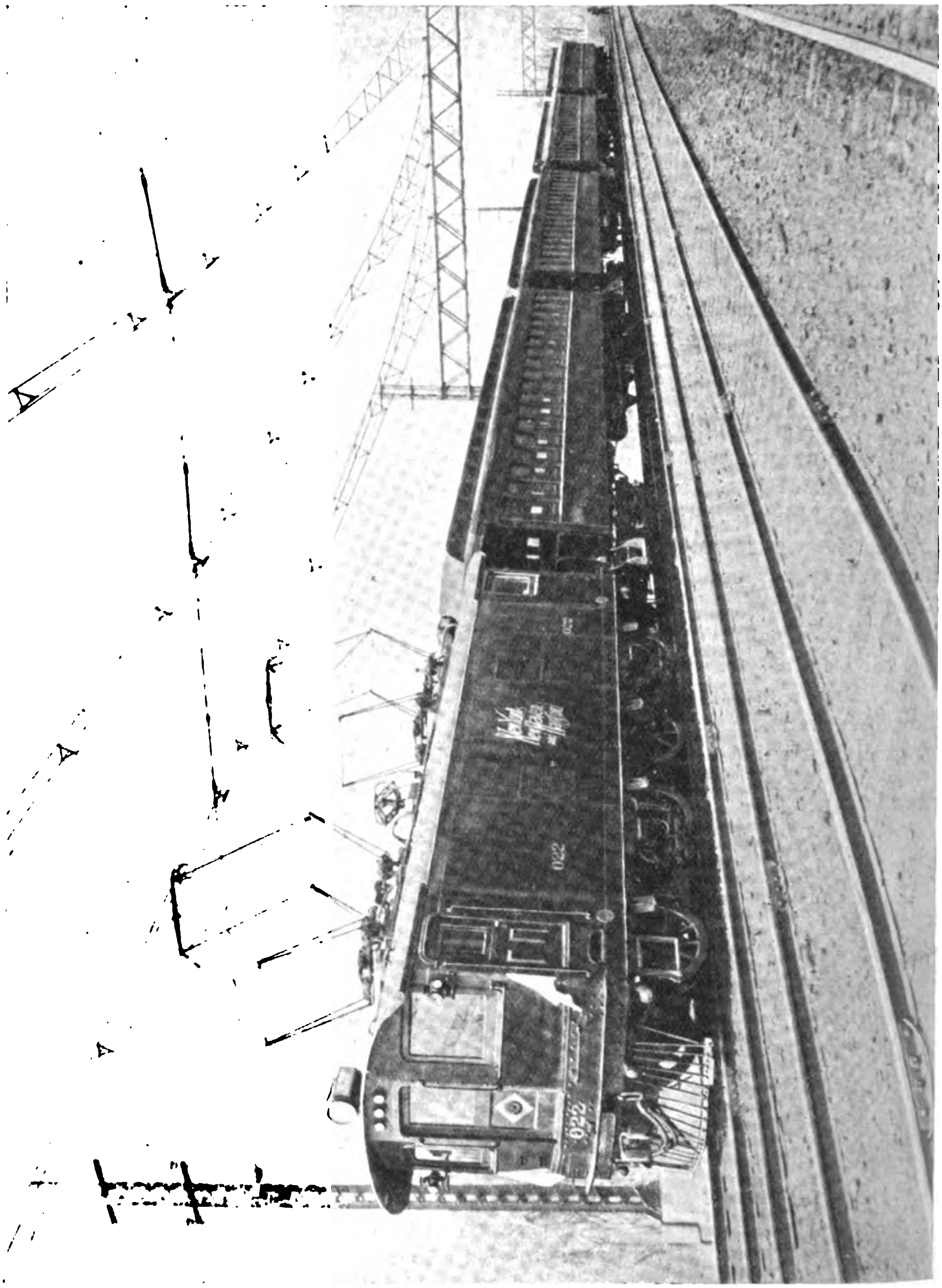


FIG. 801.—WESTINGHOUSE SINGLE-PHASE LOCOMOTIVE AND TRAIN, NEW YORK, NEW HAVEN RAILWAY, U.S.A.

Catenary Construction.—The method of catenary suspension used upon this line is novel. Steel supporting bridges span the track at intervals of 300 ft., and from these two seven-strand galvanised-steel messenger wires are suspended over each track. These messenger cables are allowed to sag 6 ft. at the lowest point between supports, and a grooved trolley wire is suspended in a horizontal position between them, as shown in Fig. 801. At curves "guy" poles are used to deflect the trolley wire and keep it within the range of the pantograph collector bows, the contact surfaces of which are 4 ft. long. One of these guy poles is seen in the illustration, and to the right of each trolley wire is seen an insulating separator, which consists simply of a rod of impregnated hickory 5 ft. long, provided with malleable-iron heads, to each end of which the pull-off wires are attached.

Under ordinary circumstances there is no difference of potential between the trolley wires, but the insulators are inserted in order that individual trolley wires may be isolated if desired. The main suspension cables are supported upon the bridges upon porcelain insulators of the skirt type, which are about 7 ins. high and 15 ins. in diameter.

Anchor Bridges.—These are provided every two miles, and are of a heavier build to take the strain of the overhead construction; they are provided with circuit breakers by which any trolley wire between any two anchor bridges can be disconnected from the supply.

Locomotives.—One of these is shown in the figure and is of considerable interest. It is carried upon two bogies, each of which is provided with two motors. Each of these motors has its armature built upon a sleeve of slightly greater internal diameter than that of the axle, and this sleeve is connected to the wheel by means of a special spring coupling. The whole of the weight of the motors it carried upon springs from the truck frame.

The motors are permanently connected two in series and receive a supply at 560 volts single phase, or when upon the direct-current portion of the track at about 650 volts. The locomotives will develop 1,000 horse power for one hour or 800 horse power continuously. The collecting devices should also be noticed, for the locomotive is provided with no fewer than three separate kinds.

The pantograph bow collectors which are seen in use, allow of an extreme variation of 4 ft. in the height of the wire. Between these may be seen a small bow or skate which is used for collecting current from the *overhead rail*, with which some parts of the line are equipped. The locomotive is also provided with four sets of third-rail shoes for collecting from the inverted third rail (*see* Fig. 793) used upon the Central Company's lines

SIMPLON TUNNEL INSTALLATION.

The electrical equipment of the Simplon tunnel has many points of interest, and is due to the enterprise of Messrs. Brown, Boveri and Co., who offered, in December, 1905, to equip the line within five months, on approval, at their own expense.

The portion of line worked electrically extends from Brigue on the Swiss side to Iselle on the Italian side, and has a total length of about fourteen miles, of which the tunnel occupies 12.5 miles. The electrical equipment is being extended upon the Italian side. The three-phase system was adopted, with a working pressure between the two overhead lines and to earth of 3,300 volts, at 16 ∿. The overhead wires are divided electrically into three sections, of which the tunnel forms one and the lines at each end the other two. Current is generated at each end at the power stations which were built to provide

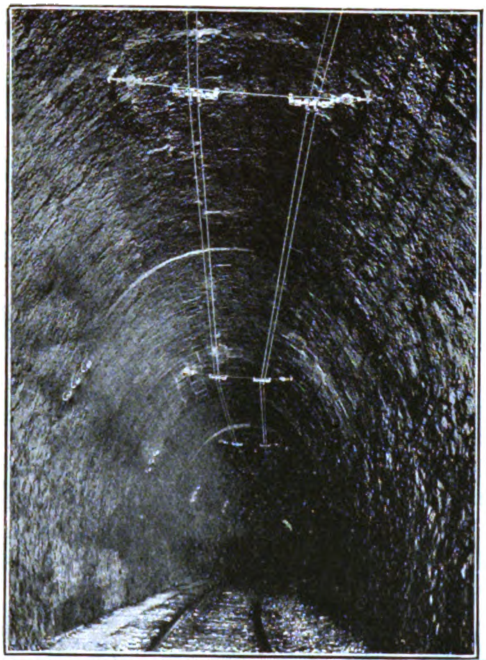


FIG. 802.—SUSPENSION OF CONDUCTORS IN THE SIMPLON TUNNEL.

(*By permission from* "*The Electrician.*")

power for boring the tunnel. Each power station supplies the section at its own end, and both supply the tunnel section.

The feeders from the power house to the lines consist of bare copper wires of $\frac{3}{8}$ in. diameter, the third phase being connected to the rails by underground cables. The rails are bonded with plastic bonds.

Overhead Wires.—Outside the tunnel the conductor consists of a single wire 0·315 in. diameter. On account of the difficulty of handling stouter wire inside the tunnel, and yet to keep down the voltage drop, two wires per phase are used, each of the same cross sectional area as that used outside. The conductors are arranged in a zigzag fashion from one cross wire to the next to equalise the wear on the collector bows and prevent grooves forming. Fig. 802 shows the method of suspension of conductors in the tunnel. Outside the tunnel the conductors are suspended in the same way by means of insulators from cross wires stretched from light tubular structures, braced together by a horizontal tie bar as shown in Fig. 803.

Insulation.—The overhead conductor is carried by means of special insulators, attached to copper-plated steel cross wires, stretched between gunmetal studs grouted into the face of the tunnel. The usual strain insulators are not used, but the cross wires are insulated from the studs at both ends by special porcelain insulators.

The insulators which suspend the conductor from the cross wires have to withstand the high working voltage under the

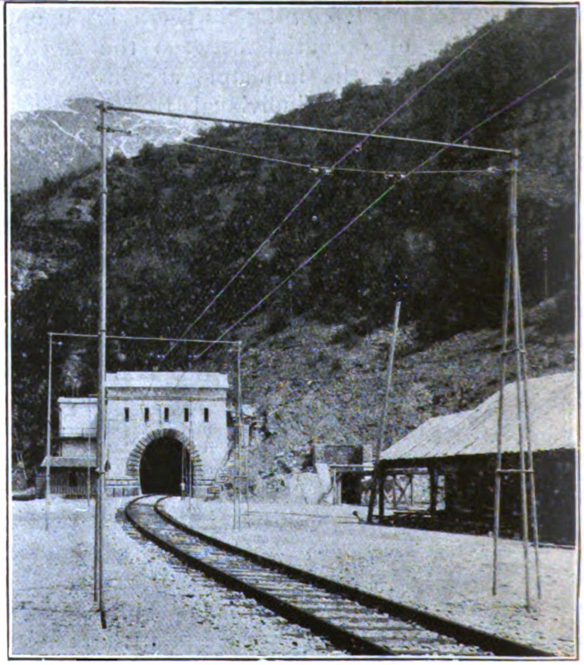


FIG. 803.—OVERHEAD CONSTRUCTION OUTSIDE THE SIMPLON TUNNEL.

(*By permission from* "*The Electrician.*")

very hot and damp conditions which obtain in the tunnel. The trolley wire is secured by means of ebonite-covered bolts to the gunmetal cross bar, the ends of which screw into bell-shaped porcelain insulators at each end, a layer of hemp and asbestos being interposed between the screw and the porcelain. These porcelain insulators screw into gunmetal end caps with a layer of rubber interposed, the end caps being secured to the steel cross wires by gunmetal clamps. This layer of rubber serves to maintain the insulation in the event of a fracture, and also imparts a small amount of elasticity. Each insulator is capable of withstanding 40,000 volts.

Locomotives.—The locomotives, Fig. 804, have five axles, viz. three pairs of coupled driving wheels, one leading axle, and one trailing, the leading and trailing being "ponies," *i.e.* pivoted like a bogie truck. The locomotives are equipped with two motors of 450 horse power each, placed between the driving axles, the drive being on to the middle axle and by means of coupling rods. The cranks, one at each end of the motor shaft, are set at right angles to one another, and balanced.

The motors are fitted with a pole changing device to give two normal working speeds of 21 and 42 miles per hour, which they will maintain though the pressure fall to 2,700 volts. The normal rated output is 450 horse power at the higher speed and 390 horse power at the lower, and they have a momentary overload capacity of 1,150 horse power. The total weight of the motors, including cranks, balance weights and connecting rods is 10¾ tons.

They have eight poles when running at the higher speed, and sixteen with the lower speed; the pole changing is as follows: The stator winding is provided with six terminals which are capable of

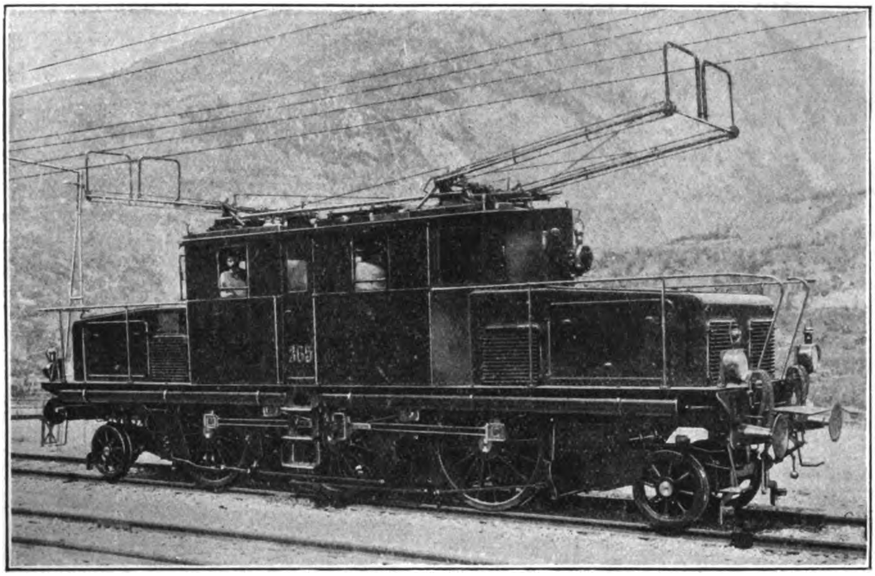


FIG. 804.—THREE-PHASE SIMPLON LOCOMOTIVE: BROWN, BOVERI AND CO.

(*By permission from "The Electrician."*)

being connected in mesh to form three circuits, making 16 poles and giving a speed of 112 revolutions per minute, or they may be star connected for eight poles, giving a speed of 224 revolutions per minute. The rotor has a six-phase winding in two groups of three each. When the number of poles on the stator is changed, the only alteration required on the rotor is that one of the sets of brushes must be raised or lowered. Figs. 805 and 806 show the stator and rotor. The total weight of the locomotive is 62 tons, 42 being available for adhesion.

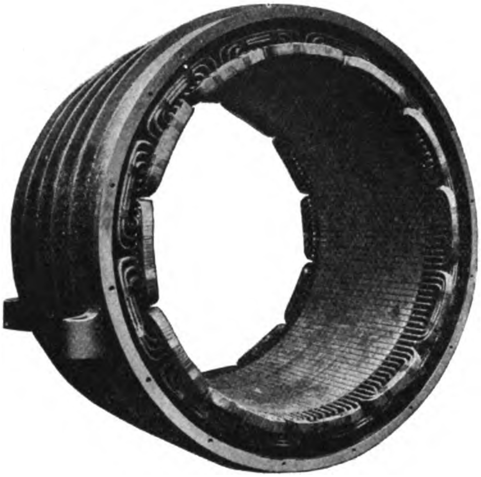


FIG. 805.—STATOR OF THREE-PHASE RAILWAY MOTOR.

(*By permission from "The Electrician."*)

Bow Collectors.—The bow used for taking current from the overhead wires is seen in Fig. 804. It is of a special pattern designed to collect current sparklessly even though the two wires are not at the same distance from the ground. The complete bow consists of two parts, the lower of which is hinged on the roof of the locomotive, and carries upon its upper end two smaller bows, which are insulated from each other and stand normally in a vertical position, but are free to swing about their lower axes. The smaller bows, therefore, take up any minor inequalities in the height of the two wires, while the lower part follows any variations in the height of the wires. The height of the wires from the rails outside the tunnel is 19 feet, while inside it is only 17 feet.

The collectors are held up in position by air pressure provided by an electrically driven compressor carried upon the locomotive, and all the electrical switches and apparatus are operated by the same means.

At points and crossings an insulated dummy wire is provided in order that the phases may not be short circuited by the bows, but these dummies are so arranged that one set of bows is always in contact with the live wires.

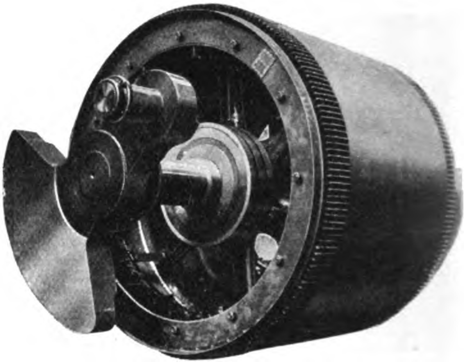


FIG. 806.—ROTOR OF THREE-PHASE RAILWAY MOTOR.

(*By permission from "The Electrician."*)

SECTION XII.

TELEGRAPHY.

CHAPTER I.—GENERAL PRINCIPLES.

SENDING AND RECEIVING APPARATUS — RELAYS — REPEATERS — CIRCUITS — DOUBLE-CURRENT WORKING — DUPLEX — DIPLEX — QUADRUPLEX — MULTIPLEX — THE SYPHON RECORDER.

We cannot in a work of this nature follow the development of the telegraph, but must confine ourselves to an outline of a few of the most commonly used systems of telegraphy. The first practical application of the electric telegraph, however, was that of Cooke and Wheatstone, who introduced their "needle" telegraph in 1837.

In modern working the line connecting two stations generally consists of a bare overhead wire carried upon porcelain insulators, and the current returns to the sending station through the earth. Primary batteries are most generally used for sending current, and various types of receiving instruments, which generally record the signals in dots and dashes or their equivalents, are in use. In the international Morse code, which is almost universally used for telegraphy, the alphabet, numerals, and other necessary characters are made up of combinations of dots and dashes, and the messages are therefore sent in this form to the receiving end, where they are re-translated by the operator. The Morse alphabet is given in Fig. 807.

ALPHABET.						NUMERALS.	
A	· —	**K**	— · —	**U**	· · —	**1**	· — — — —
B	— · · ·	**L**	· — · ·	**V**	· · · —	**2**	· · — — —
C	— · — ·	**M**	— —	**W**	· — —	**3**	· · · — —
D	— · ·	**N**	— ·	**X**	— · · —	**4**	· · · · —
E	·	**O**	— — —	**Y**	— · — —	**5**	· · · · ·
F	· · — ·	**P**	· — — ·	**Z**	— — · ·	**6**	— · · · ·
G	— — ·	**Q**	— — · —	**Full Stop**	·· ·· ··	**7**	— — · · ·
H	· · · ·	**R**	· — ·	**Repeat**	· · — — · ·	**8**	— — — · ·
I	· ·	**S**	· · ·	**Hyphen**	— · · · · —	**9**	— — — — ·
J	· — — —	**T**	—	**Apostrophe**	· — — — — ·	**0**	— — — — —

FIG. 807.—THE SIGNS OF THE MORSE CODE.

INSTRUMENTS.

The Single-needle Instrument.—In this instrument a small magnet is pivoted upon an horizontal arbour, and weighted so as to hang vertically. On either side of the magnet a coil is placed, having its axis in the plane in which the magnet is free to swing, as shown in Fig. 808. Upon the passage of a current, therefore, round the coils, the magnet is deflected to the right hand or the left, the direction of deflection depending upon the direction of the current. These coils have a resistance of 200 ohms and require from 15 to 20 milliamperes. The apparatus described is usually enclosed, but the arbour moves a small pointer which can be observed by the operator.

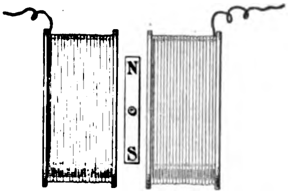


FIG. 808.—COILS FOR SINGLE NEEDLE.

The small magnet is now generally replaced by a piece of soft iron moving between the poles of a powerful permanent magnet and thus magnetised by induction. This arrangement has the advantage that the operating magnet is not liable to have its polarity reversed by lightning discharges.

A deflection of the top of the needle to the right corresponds to a dash, and to the left to a dot, and the instrument may therefore be read by watching the deflections of the needle. The motion of the needle is limited in either direction by two stops, to which are frequently attached two short pieces of tube, which when struck by the needle give out different notes; the operator is thus able to read the messages by the sound without looking at the needle, and this results in much greater speed of working.

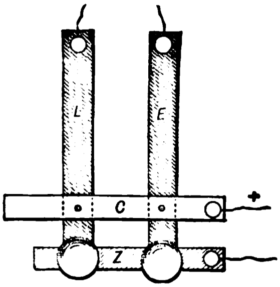


FIG. 809.—TAPPER.

The Tapper Key.—The principle of the "tapper" or commutator by which the direction of the current through the line is controlled is shown in Fig. 809. Two keys L and E are connected to line and earth respectively and normally rest against a metal contact C which is connected to the carbon terminal of a battery. The other terminal is connected to the contact Z which lies below the keys L E, but out of contact with them. Normally no current flows, but when the E key is depressed, its contact with the C terminal is broken and it makes contact with Z, the current therefore flows from C to line, through the receiving instruments to earth and back through earth to the zinc pole of the battery. If the L key is depressed the direction of the current is obviously reversed. Fig. 810 shows a simple circuit with sending and receiving station.

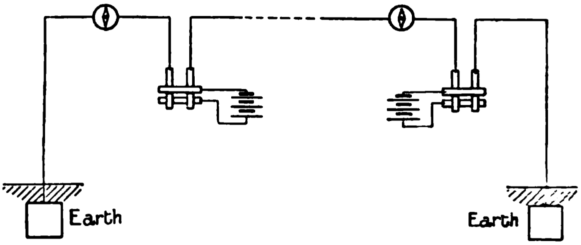


FIG. 810.—SINGLE NEEDLE CIRCUIT.

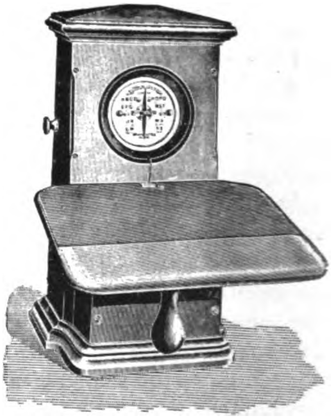


FIG. 811.—SINGLE NEEDLE INSTRUMENT.

The Drop Handle.—Another device which is more largely used for the same purpose is known as a "drop handle"; in this arrangement metal segments are carried upon a barrel of insulating material against which spring contacts press and make the necessary connections when the barrel is partially rotated by means of a handle attached to the end.

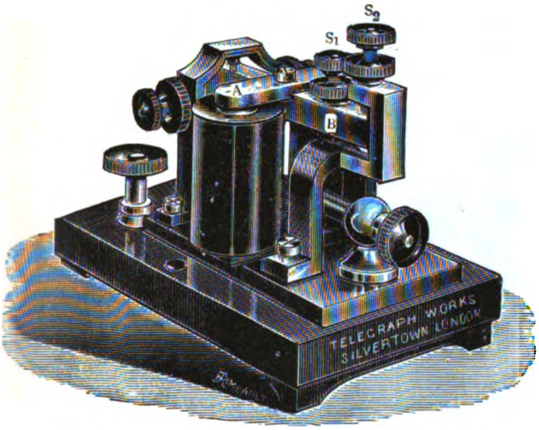


FIG. 812.—THE P.O. SOUNDER.

Fig. 811 depicts a drop-handle instrument, the receiving needle or pointer being clearly shown.

The Sounder.—This instrument, which is shown in Fig. 812, is the simplest of all telegraphic instruments in use. It consists merely of a double-pole electromagnet, above the poles of which an iron armature A is supported upon a brass lever B. The motion of this lever is limited by means of two adjustable stops S_1 S_2, and it is normally held against the upper of these by means of a spring. Upon the passage of current through the coils of the magnet the armature is attracted and pulls down the lever with a smart blow against the lower stop, thus emitting an audible sound; directly the current ceases the lever returns to the upper position under the action of the spring. Two sounds are therefore emitted by this instrument, but they are always given alternately, and are not dependent upon the direction of the current, and therefore the method of signalling used with the needle instrument requires modification. With this instrument the *time* during which the current flows, and consequently between the two clicks of the sounder, distinguishes the signals. The shortest signal is the dot, while one three times as long represents a dash. The interval of time between two elements of a letter is equal to *one dot*, that between two letters is equal to *three dots*, that between two words is equal to *six dots*.

Morse Ink Writer.—The principle of this instrument is similar to that of the one just described, and may be gathered from Fig. 813. The armature A is carried upon the lever L, one end of which is pivoted at P, and the other end lies between two stops S_1, S_2, being normally held against the upper stop S_1 by an antagonistic spring S, the tension of which is adjustable. A light arm from the other end of the lever carries the small metal disc D, the lower edge of which just dips into an ink-well. Immediately above the metal disc a strip of paper, about half an inch wide, is passed at a constant speed by clockwork, which is released by the motion of the lever.

The action of the instrument is now obvious, for when the armature A is attracted by the electromagnet, the disc D is raised into contact with the paper strip, and remains so as long as current passes, thus marking a dot or dash according to the duration of the current. With this machine, therefore, a permanent record of the signals is obtained, which can be read off at leisure. A complete instrument is shown in Fig. 814.

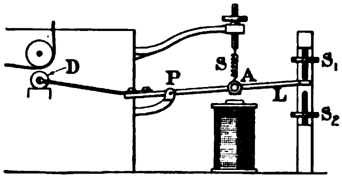


FIG. 813.—MORSE INKER.

The Morse Key.—With these instruments the only transmitting apparatus necessary is a Morse key, such as that shown in Fig. 815. The lever, which is pivoted centrally, is connected to the line wire, and is normally held by means of a spring against the back contact. By depressing the key this contact is broken and connection made with another contact in the front of the lever. The connections for such a key are shown later.

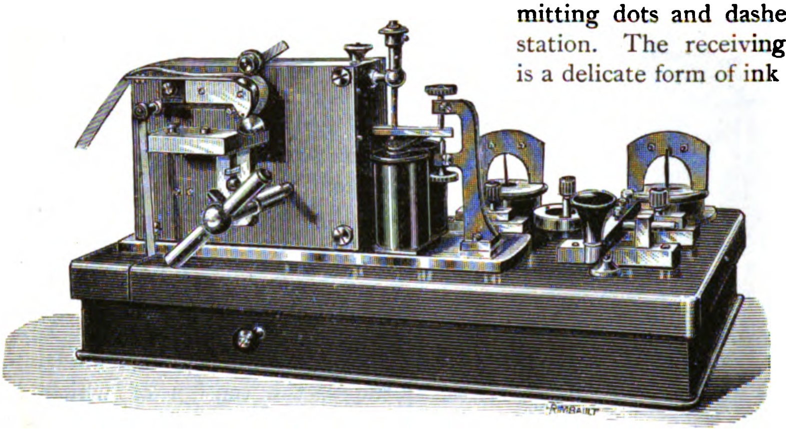


FIG. 814.—MORSE INK WRITER AND KEY.

OTHER SYSTEMS.

Besides the instruments mentioned above many others are in use, among which may be mentioned the Wheatstone A B C, in which the message is spelled out by a pointer indicating the letters upon a dial; and the Hughes typewriter, in which the messages are transmitted by pressing notes corresponding to the letter or figure required, and printed at the distant station in clear Roman type. An instrument has also been invented for transmitting handwriting electrically.

There is another apparatus, namely, the Wheatstone Automatic, which is very largely used in England, and which has resulted in a great increase in the possible speed of transmission, and the elimination of the errors due to human labour. In this system the message is first written upon a strip of paper by means of perforations which correspond to the Morse letters, and this strip is then passed at a high speed through the transmitter, where the perforations are the means of transmitting dots and dashes to the receiving station. The receiving instrument used is a delicate form of ink writer. With this apparatus a speed of 400 words per minute or more can be obtained, whereas hand-operated instruments only attain a speed of from 20 to 30 words per minute.

Mr. Barclay, of the Western Union Company of America, has within recent years greatly improved the Wheatstone system. In his arrangement a typewriter operates a perforating machine electrically, and the perforated strip sends signals to the line in the ordinary way, but these signals operate a machine at the receiving end, which prints Roman type upon the forms ready for delivery. Messages can thus be sent at the rate of 100 words per minute, and the system has the great advantage that no skill beyond that of an ordinary typist is required for its operation. This results, of course, in a great reduction of operators' wages.

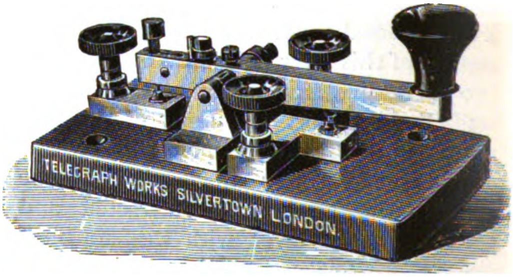


FIG. 815.—MORSE KEY.

RELAYS.

Another piece of apparatus which plays a most important part in telegraphy is the relay; its function is to enable a current, too feeble to operate a receiving instrument itself, to bring into action a more powerful "local battery" to do that work.

The action of the simplest form of relay is shown in Fig. 816. The beam B is normally held by the spring S against the pin K_2, but upon the passage of a current through the coils of the electromagnet M the armature A is attracted and raises the beam B into contact with K_1. Evidently, then, if the local battery is connected to B and K_1, its circuit will be completed when current flows through the coils of M; if to B and K_2, it will only be complete when no current flows through M.

Fig. 817 shows the application of a relay, and it will be clear from this diagram that the signals recorded by the local battery correspond exactly to those feeble ones received by the relay.

Polarised Relays.—The relay above described is of the non-polarised type, that is to say, its armature is not normally magnetised. The relays used are, however, generally of the polarised type, as these are more sensitive and are dependent upon the direction of the current. The Post Office standard pattern of relay consists of two vertical bar electromagnets, between the top and bottom pairs of poles of which, two soft iron tongues, magnetised by a permanent magnet, are free to play.

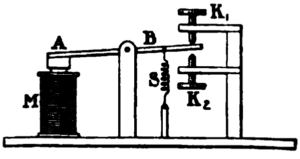


FIG. 816.—SIMPLE RELAY.

The coils of the electromagnets are so wound that upon the passage of a current both tongues move over together to one side or the other (depending upon the direction of the current in the coils) and complete the local circuit.

REPEATERS.

When long telegraph lines are in use the difficulty of getting sufficient current to operate the receiving instruments through to the far end becomes considerable, for the resistance of the line is great, and there is considerable leakage. This difficulty can, of course, be met in some measure by increasing the battery power, but it is undesirable to do this to any great extent as the strain upon the insulation is increased, as are also the variations due to changes of weather. In England it is found difficult to work direct for more than about 400 miles, but in drier climates the distance is considerably increased.

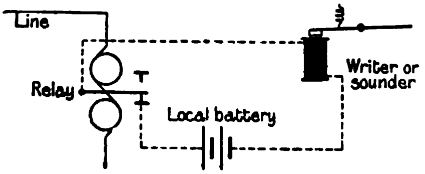


FIG. 817.—LOCAL CIRCUIT.

In all countries, however, a distance is reached at which it becomes necessary to take the message and re-transmit it. This can be done in two ways: firstly, by reading the message and repeating it by hand, secondly, by the use of a *repeater* or *translator.*

The function of a repeater is similar to that of the relay, but with this difference, that while the relay is used to complete the circuit of a local battery to operate a receiving instrument at the same station, the repeater is used to re-transmit to a distant station. Relays are used at the repeater station and these complete the local battery circuit, which in turn operates the repeater. The transmitting instruments are essentially sounders, of which the lever takes the place of the beam, and the contacts between which it plies, that of the back and front contacts of the Morse key.

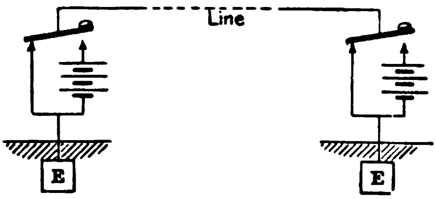


FIG. 818.—OPEN CIRCUIT.

By means of such repeaters messages can be transmitted any distance; the line, for instance, from London to Teheran, which is 3,800 miles long, is so worked entirely without hand repetition. The speed of working of a long line is also greatly increased by the use of one or two repeaters.

CIRCUITS.

There are two distinct methods of working a telegraph circuit, and these are shown in Figs. 818 and 819. Fig. 818 shows the *open circuit*, which is almost universally used in England, and in which the current is only flowing when a message is being sent. Fig. 819 shows the *closed circuit*, which is used in America, Australia and elsewhere, and in which the current is always flowing unless interrupted to send a message.

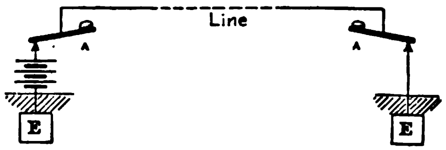


FIG. 819.—CLOSED CIRCUIT.

Open Circuit Working.—With a single-needle instrument, an open circuit is always used. The simple connections for two stations are shown in Fig. 810, but several of these instruments may be connected in series by simply carrying the connection from B (Fig. 810) to another station instead of to earth, and it will be evident that by depressing the keys at any station *all* the needles are operated, though the message need, of course, only be read at one. These instruments are largely used for connecting villages with the larger towns, and are very satisfactory for that purpose, as very little skill is required to operate them, and they require no adjustment for variation of current due to change of resistance of the line or battery variation. The connections for three sounder instruments are shown in Fig. 820, and it will be seen that by depressing either key all the sounders respond, except that at the transmitting station, where the galvanometer G shows the operator whether his current is going correctly to line. Such open circuit working without the use of relays is called *direct working* and is used where the total resistance of the circuit, including the apparatus, does not exceed about 200 ohms. The current to work such a circuit is from 90 to 100 milliamperes. For longer circuits the connections shown in Fig. 821, involving the use of relays, are adopted.

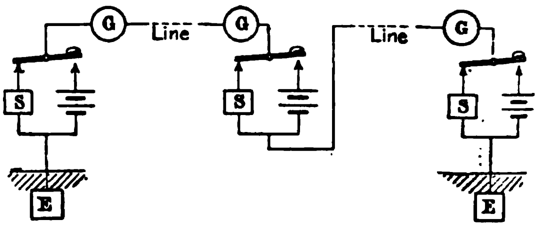


FIG. 820.—SOUNDERS IN SERIES.

It is unusual in England to work more than four sounders in series upon the same line, as with this number the line is generally fully occupied during the busy hours. Where there are a sufficient number of messages to be sent a line merely connects two instruments, and this is the simplest and most satisfactory arrangement possible.

Closed Circuit Working.—Fig. 822 shows the connections for working sounders upon a closed circuit (the relays only being shown). In this system only one battery is necessary, and the current from this is normally flowing in series through all the relays. Suppose, however, that station B wishes to send a message, he opens the circuit by means of the switch shown, thus converting it to an open circuit, and then proceeds to signal. The main difference between this circuit and the ordinary open circuit is that the current is always derived from the same battery, and that the operator's signals are given on his own instrument as well as all the others. To receive, the operator must again close his switch.

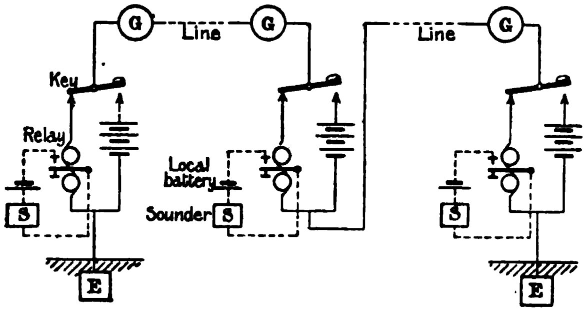


FIG. 821.—RELAYS IN SOUNDER CIRCUIT.

The advantages of the closed circuit are that as the current is always derived from the same battery, the current at a given station is constant, and consequently the adjustment of a number of Morse instruments in series is easier, as many as fourteen having been in some cases thus used. There is also only one battery to keep in order, though this is sometimes distributed along the line in order to compensate for leakage to earth.

Under the conditions which obtain in England, where many Morse instruments are never used in series, and where the wire is only busy during a few hours of each day, the system, though it has frequently been tried, has not been found to possess sufficient advantages to warrant the increased consumption of battery materials, and has generally been abandoned.

Double - Current Working.—When underground or submarine cables form part of the line there is a considerable capacity effect (*see* page 372), for the conductor of the cable corresponds to one coating of a Leyden jar, the insulation forms the dielectric and the earth the other coating. The same effect occurs to a lesser extent with overhead lines, the air in this case being the dielectric.

This results in a diminution of the speed at which signals can be transmitted through the line, for each time the circuit is completed the line has to be *charged*, and discharged each time the circuit is earthed, and as each takes an appreciable time, the signals become confused unless sent slowly. A similar retarding effect will also result if the circuit has a large self-induction (*see* page 198). To overcome this, double current working is used upon long underground lines or on lines containing intermediate Morse or sounder instruments. After each "marking" current a "spacing" current of opposite polarity is sent, and this has the effect of neutralising

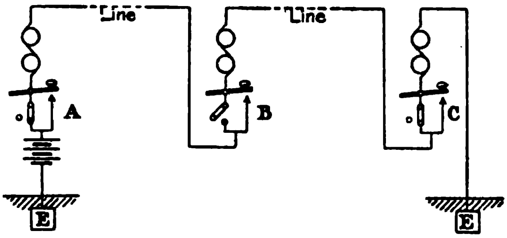


FIG. 822.—CLOSED CIRCUIT CONNECTIONS.

the residual charge, and thus increasing the speed of working. The spacing current is generally provided by the same battery as the marking current, a special form of key being used to effect the reversal.

With double-current working polarised relays are essential in order that they may not be worked by the spacing currents, but as these relays are always held by the current in one position or the other, no other controlling force is necessary, and they are therefore very sensitive. Other advantages of double-current working are that it eliminates the effect of residual magnetism in the receiving relays, and the effects of variation of the receiving current are reduced as both marking and spacing currents are equally affected.

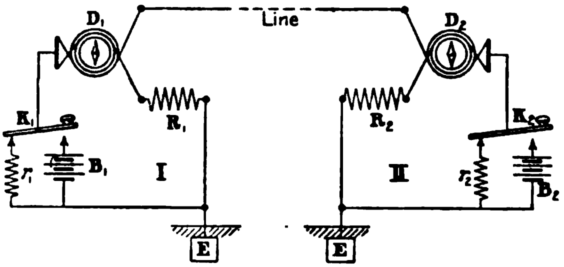


FIG. 823.—DIFFERENTIAL DUPLEX CIRCUIT.

DUPLEX WORKING.

By means of duplex working it is possible to transmit two messages simultaneously in opposite directions over the same wire. There are two main methods of doing this, *i.e.* differential duplex and bridge duplex.

Differential Duplex.—This method requires the use of specially wound *differential* receiving instruments; that is to say they are wound with two identically similar coils so arranged that they neutralise each other's effects if equal currents are passed through each coil simultaneously in opposite directions, but respond if current passes through one coil only. The principle upon which the working depends is that if two paths are open to a current it will divide itself between them inversely as the impedance (*see* page 370) of each.

Fig. 823 gives the connections in diagrammatic form, where D_1, D_2 represent the differentially wound receiving instruments and B_1 B_2 the batteries which should be exactly similar. The resistances R_1 R_2 forming the "compensation circuit" are adjustable and are made equal to that of the line and those parts of the receiving instruments connected to it.

Suppose now that the key at station I is depressed. Two paths are open for the current, *i.e.* through the line and earth return, and through the compensation circuit; and since the resistance of each of these is equal the current flowing through each coil of D_1 is equal, and consequently there is no deflection. The current going to line, however, traverses one coil of D_2 and then has two paths to earth open to it, one through the low resistance R_2 and the other through the high resistance R_2. The larger current therefore goes to earth *via* r_2, and some also goes through R_2, traversing both coils of D_2, but from the diagram it will be evident that these currents both tend to produce the same effect and not to neutralise each other: D_2 therefore responds. A similar effect would of course result if K_2 were depressed while K_1 was normal. So far we have only supposed the stations working as simplex stations and seen that each receiver is unaffected by signals sent from its own end; but suppose now that both keys are depressed at once, the currents flow in the compensation circuits as before, but in the line circuit two batteries of equal E.M.F. are opposed, and therefore no current flows in the line or the instrument coils connected thereto, with the result that the compensation circuits are enabled to produce a signal. By this means then the signals sent from one end are under all conditions received at the other, although when both are signalling no current actually traverses the line.

Bridge Duplex.—The differential principle just described depends upon balancing the *currents* in the two circuits, the bridge method consists in balancing the *potentials* at points in the circuits. The diagram is shown in Fig. 824, and the similarity to the Wheatstone Bridge (page 320) will be at once apparent. R_1 R_2 are artificial cables, made of resistances and condensers. A B, A C are resistances and are so adjusted that the resistances are in the following ratios:

$$\frac{AB}{AC} = \frac{\text{line and connections}}{R_1}$$

Upon depressing the key at I therefore no current flows through the instrument G_1, for the fall of the potential down A B equals that down A C, and therefore there is no difference of potential between B and C. The current which goes to line divides at D and flows partly through F and r_2 and partly through G_2, thus producing a deflection. When both keys are depressed the potentials at B and D being equal no current flows in the line but, the potential balance being upset, current flows through the circuits A B C and F D E and gives signals at each end.

The value of the current sent to line may be increased by increasing the resistances in A C and R_1 but the current passing through the instrument will be diminished; the A B and A C resistances are often made equal (in the Post Office form 3,000 ohms each) in which case R_1 must be equal to that of the line and receiving instrument. The bridge method of duplex working may be used with any form of receiving instrument, and when suitable condensers are used permits of more rapid signalling through cables than does the differential method, but it requires a larger battery power and has no advantage for overhead lines.

DIPLEX.

Diplex working consists of sending two messages simultaneously over the same wire in the same direction. It depends upon the use of two receiving relays, one of which is affected by a change in the *direction* of the current and the other by a change in the *strength* of the current; it requires special transmitting keys.

QUADRUPLEX.

Edison in 1874 combined duplex and diplex working to form a practical quadruplex system by which two messages can be sent in each direction at the same time.

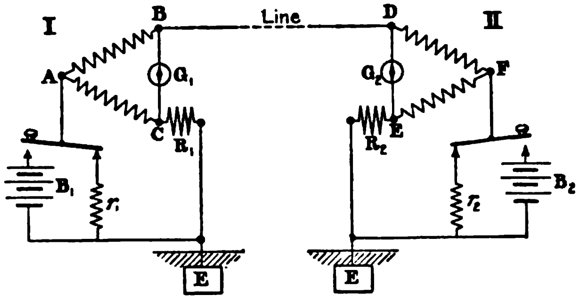


FIG. 824.—BRIDGE DUPLEX CIRCUIT.

Two batteries are used, one being larger than the other. In the normal position of the sending keys the negative pole of the smaller battery is connected to line and sends a small current through the relays at the receiving end. One of the relays is polarised, has no controlling spring, and is sufficiently sensitive to respond to a change in direction of this small current. The other relay is not polarised and is provided with an antagonistic spring which is so adjusted that the relay will not respond to the small normal current. Fig. 825 shows the arrangement of batteries and sending keys, which are shown in the normal position. K_1 represents the *reversing* key and K_2 the *increment* key; the contacts shown at K_1 are carried transversely at the end of a key similar to that shown at K_2. It will be seen from the connections that if K_1 alone is depressed (*i.e.* the contacts shown raised) the current from B_1 is reversed, working the polarised relay only. If K_2 alone is depressed B_2 is thrown into circuit without reversal of current, and the non-polarised relay only responds. If both keys are depressed at once, both batteries are thrown in series into circuit and reversed, thus working both relays. The contacts upon K_2 should be set so that the circuit is broken for the least possible time, otherwise the polarised relays will be affected. The resistance S is to prevent sparking at the contacts of K_2, and S_1 to keep up the resistance of the whole circuit when B_2 is cut out.

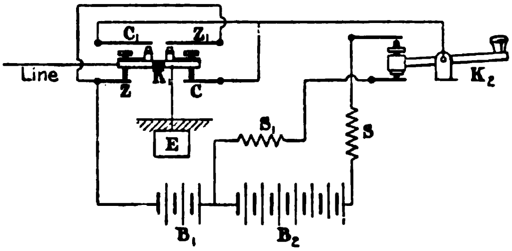


FIG. 825.—CONNECTIONS OF KEYS FOR QUADRUPLEX WORKING.

The line may also be split if necessary, and continued in two different directions as two duplex circuits.

MULTIPLEX.

Multiplex is the name given to those systems by which several messages may be sent simultaneously in either direction over one wire.

The principle of working is, however, quite different to that of duplex and quadruplex given above. It is largely mechanical, as may be gathered from the diagram, Fig. 826. The line wire is connected at each end to rotating arms which move over a number of metallic segments. The arms are made to move in synchronism at considerable speed, and each segment is thus connected to the line a number of times per second. Transmitting and receiving instruments are connected to corresponding segments at each end, and upon the key connected to, say segment No. 1 at A, being depressed, a number of impulses per second are sent to segment No. 1 at B, and there recorded upon the receiving instrument.

The above is only intended to indicate the principle upon which multiplex working depends, and many essential details have been omitted.

THE SYPHON RECORDER.

The high resistance and capacity of submarine cables render many modifications in the ordinary methods of telegraphy necessary, and among others the use of a very delicate receiving instrument. The instrument first used was the Thomson reflecting galvanometer.

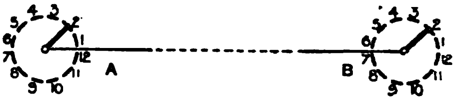


FIG. 826.—MULTIPLEX DIAGRAM.

The Kelvin syphon recorder, which is now universally used, is a modification by Lord Kelvin of his original instrument. The suspended coil moves a small syphon by which ink is carried from a reservoir and directed upon a strip of paper moved before it. The coil is connected to the syphon by means of fine cocoon fibres, and thus deflects the jet from one side to the other of the central position according to the signal sent from the sending station. The result is, therefore, a wavy line upon the paper from which the signals may be read.

CHAPTER II.—ELECTRIC OSCILLATIONS.

PRODUCTION OF ELECTRIC OSCILLATIONS—OSCILLATORY NATURE OF SPARKS MADE VISIBLE AND AUDIBLE—PROPERTIES OF ALTERNATING CURRENTS OF VERY HIGH FREQUENCY —OSCILLATION TRANSFORMERS.

Owing to the excellent literature extant relating to land and submarine telegraphy, and to the comparative paucity of works dealing with wave telegraphy, the author has deemed it advisable to dismiss the former with a brief reference in order to permit of dealing with wave or "wireless" telegraphy in a more comprehensive manner. What follows is, therefore, somewhat of a survey of the operations and principles of wave telegraphy, although space forbids anything in the nature of detailed treatment.

In this section the history of the work done before the practical application of Hertzian waves was known must be only briefly mentioned, for, whatever may be the ultimate principles made use of, the ætheric-wave telegraphy of to-day puts methods depending upon leakage and ordinary magneto-electric induction quite out of court.

In dealing with radio-telegraphy much that is important must be left out, but an attempt is made to give a general sketch which will embody most of what is essential with as much detail as possible in the space available.

It has further seemed advisable to give a complete detailed account of one system. In making the selection, the writer has had to consider general interest and practical importance as well as ease of access to information ; therefore choice was made of the Lodge-Muirhead system, in which sealed boxes and patented "secrets" are non-existent.

This system is doing excellent work and steadily extending its range of practical utility by sheer merit, without the aid of gratuitous press advertisements.

PRODUCTION OF ELECTRIC OSCILLATIONS.

It has been shown elsewhere that every circuit of capacity and self-induction has a natural period of electric vibration unless the resistance of other portions of the circuit is above a certain critical value.

Comparison has also been made between the maintenance of steady electrical and mechanical oscillations at a fixed amplitude by the application of small, timed impulses, and it is this effect which makes electrical tuning or syntony possible in wireless telegraphy.

It is, however, with the first-named effect that we are now concerned, and, before going further, we may again discuss the conditions of its working.

In all cases of natural rhythmic vibration, two properties of the oscillating system come into play in combination. One is the *force tending to restitution*, the other is *inertia*, or the tendency of a body to continue in an unchanged state of motion. The originating cause of the oscillations is a force of displacement.

The weighted spring is a typical example, and we will use its component parts to illustrate the above statement. If pressure be applied to a vertical strip of springy steel in such a way as to bend it out of its position of rest, the new position taken up by it is such that its elastic force is equal and opposite to the impressed force. The displacement of the spring is directly proportional to the force applied to it and inversely to its elasticity; if the pressure were removed and the spring had neither a weight at its end nor mass of its own, it would fly back to the central position and stop there, but the second property comes into play. The inertia of a body is its tendency to remain in whatever state of motion it exists, and no change of motion can take place without either the absorption or emission of energy.

Before the spring is released, the energy stored by the spring is potential, and during the return to the central position it is given up to the weight which, by its inertia, retards the movement. At the moment of crossing the central point there is no strain in the spring, the whole of the energy not used against friction having been transferred to the weight by virtue of its motion; in this kinetic form the energy carries the mass past the centre to the other side. The movement is at once opposed by the spring in which the kinetic energy transferred from the weight again gradually becomes potential, the transference being complete when motion ceases.

When this process has again taken place, but in a reverse direction, bringing the weight to its furthest point on the side from which it started, a complete cycle has been performed.

Each swing is less than the last by an amount depending on the friction, and the vibrations gradually die away without significant alteration of period, until the whole is at rest.

We may make a comparison between the electrical effects with which we are concerned and an imaginary mechanical example. (The addition of the brittle diaphragm to this illustration is due to Professor Northrup.)

In Fig. 827, two circuits, A and B, are shown; A is made up of pipes and chambers containing some heavy liquid, with a cylinder and piston C to produce a difference of pressure between the two sides of the circuit. The liquid is prevented from flowing through either of the chests D and E by water-tight diaphragms F and G; G is of india-rubber or other elastic fabric, F of a brittle substance incapable of elastic distension, and of such strength that when the pressure becomes sufficient to distend G to some definite distance (*e.g.* to the dotted line on the right of its central position) it completely breaks down, giving free passage for the flow of the liquid.

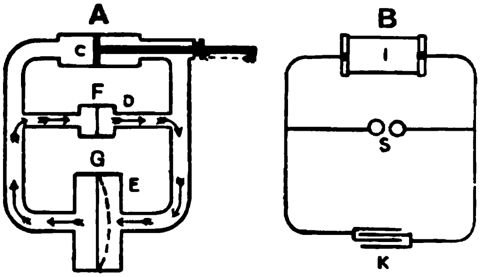


FIG. 827.—ANALOGY BETWEEN WATER AND ELECTRICAL CIRCUITS.

On applying an increasing pressure in the direction of the dotted arrow, the diaphragm distends until it reaches the dotted line on the right, at which point the brittle diaphragm F breaks down. A quantity of liquid proportional to the pressure and to the "stretchability" of G is stored in its bulge, and, the release at the diaphragm F is followed by a flow of liquid in the direction of the arrows, the energy stored by the diaphragm G being given up to the liquid until G has straightened itself.

At the moment of zero-pressure the liquid is moving with maximum velocity and overshoots the mark, causing a bulge to the left. A reversal of flow follows, and so the liquid surges back and forth through the pipes until the oscillations die away by reason of the friction.

Corresponding to G there is in the circuit B the glass or other dielectric of the condenser K, which behaves as if electrically elastic (*see* page 11); if, therefore, a high voltage be applied to it by means of an induction coil I, an electrical displacement takes place and is proportional to the electrical "stretchability" of the dielectric. As in the hydraulic case the displacement is directly proportional to the pressure applied.

The counterpart of the brittle diaphragm is the spark-gap S, which has a very small capacity in comparison with the condenser, and breaks down when the voltage rises to a sufficiently high value.

When once established the electric spark is a very fair conductor, and may be looked upon as a passage suddenly opened for the flow of electricity. The analogy is thus complete. In the electrical case the piercing of the air gap is immediately followed by a rush of current. The current builds up an increasingly strong magnetic field round the conductors, and this field is strongest at the moment of maximum-current strength and of zero difference of potential between the two condenser-coatings. Now the magnetic field begins to collapse and cut the wire, producing an E.M.F. which tends to maintain the flow of the current; this consequently overshoots the mark, charging the condenser in a direction opposite to that of the initial charge. When the flow has ceased the condenser produces the reverse rush, and the current, again overshooting the mark, charges the condenser in the original direction, but to a lesser degree. The cycle repeats itself several times, each maximum of current and of charge being less than the last, until the oscillations die away and the spark is extinguished.

All this occurs in a very small fraction of a second, for if a circuit has a natural frequency of 800,000 per second and performs 20 complete cycles before dying away, the period during which the whole set of oscillations takes place from the first full charge to the final condition of rest, is $\frac{20}{800,000}$ of a second.

In 1847 Helmholtz conjectured that condenser discharges could be oscillatory, and a mathematical demonstration by Lord Kelvin followed in 1853. Feddersen gave the first experimental verification in 1859.

OSCILLATORY NATURE OF SPARKS MADE VISIBLE AND AUDIBLE.

Electrical evidence of the oscillatory character of sudden condenser discharges through inductive circuits abounds, but more direct proofs may be mentioned.

Under certain conditions the alternate maxima of current occurring every half period cause very rapid expansions and contractions of the air which result in trains of sound-waves.

The electrical vibrations ordinarily dealt with range from a few hundred thousand to a few thousand million per second, and it is impossible to make any audible tone by this means unless the frequency is enormously lowered, as the highest musical note which the human ear can appreciate is given by vibrations to the number of 70,000 per second.

Sir Oliver Lodge actually produced a spark which emitted a note something like the squeak of a bat. The pitch of the note was variable by adjusting the self-induction.

The oscillatory nature of the discharge

can also be demonstrated with the aid of rotating mirrors.

Fig. 828 shows a remarkable and interesting photograph of an oscillatory spark taken on a revolving photographic plate ; it is published by kind permission of Mr. C. J. Watson, of Birmingham, who took the original photograph with very ingeniously contrived apparatus.

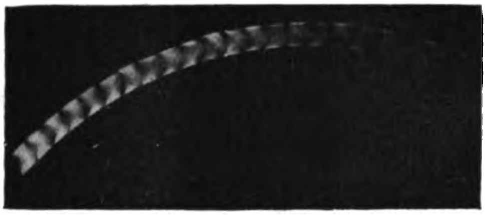


FIG. 828.—AN OSCILLATORY SPARK.

(From a photograph by C. J. Watson.)

CONDITIONS GOVERNING PRODUCTION AND FREQUENCY OF OSCILLATIONS.

Let us return to the original analogy of the weighted spring which can be maintained in motion by the application of small timed impulses ; the sum total of work done by these impulses in a given time is equal to the work expended by the weight and spring in overcoming air and other friction. If there were no friction the spring would vibrate for ever; similarly if resistance and all other losses could be eliminated from an electrically vibrating circuit, the current would oscillate for ever.

The rate at which the amplitude decreases (known as the damping) depends upon the rate at which work is done, and a sufficient rate of energy-expenditure would prevent oscillations from taking place at all. A weighted spring immersed in treacle and deflected would merely return to the position of rest gradually without overshooting the mark. Similarly, if a slightly wetted thread of very high resistance were substituted for the spark-gap in an oscillatory electric circuit the circuit would only permit the passage of a gradually diminishing unidirectional current. The discharge must occur suddenly as any brush discharge, spitting-off, or other leakage taking place prematurely, meets with a high resistance and cannot be of an oscillatory character. If the brittle diaphragm in the hydraulic circuit of Fig. 827 gave way gradually, allowing small jets of liquid to pass before the complete breakdown occurred, these jets would not be oscillatory and would reduce the energy available when the actual surging took place. The degree of enfeeblement would depend on the volume of liquid held by the bulging diaphragm.

Much needless discussion as to the polishing of spark-balls for oscillatory discharges, has arisen, Sir Oliver Lodge and others having found that a high polish is very important at the sparking surfaces of small oscillators ; others using larger oscillators have denied the necessity.

Both statements are right, for small oscillators have a very low capacity, and therefore if preliminary brushes, electric winds, etc., were not prevented by polishing, there would be but little left of the original charge when the final rush occurred.

Where the capacity is large, as in the case of a Leyden-jar circuit or a wireless telegraphy aerial, a small loss occurring previously to the passage of the main discharge is an insignificant percentage of the whole energy accumulated.

If the only energy loss is that due to resistance, oscillations cannot take place if R be greater than

$$\sqrt{\frac{4L}{K}}$$

Damping may also result from dielectric hysteresis (*see* page 844) in the insulating medium of the condenser, and at very high frequencies this develops considerable heat. There is also damping by the inductive transfer of energy to neighbouring conductors; but the most important cause in the case of electric-wave generators is radiation. However we are momentarily more concerned with those oscillations which do not produce significant radiation.

The frequency of an oscillatory circuit is given by the expression

$$2 \pi n = \sqrt{\frac{1}{KL} - \frac{R^2}{4L^3}}$$

PROPERTIES OF ALTERNATING CURRENTS OF VERY HIGH FREQUENCY.

Choking Effects.—The experimental demonstrations of the extraordinary choking effects of small self-inductions at high frequencies are very striking. If the discharge be sent through a single turn of a foot or two of thick copper rod, the voltage between the ends of the turn is sufficient to cause a spark even if the ends are separated by a quarter of an inch. The discharge prefers to take an air gap of a quarter of an inch rather than a foot or two of thick copper rod.

To produce such a spark about 18,000 volts are required, and a *continuous* voltage of 18,000 maintained across three feet of $\frac{1}{4}$ in. copper rod would produce a current of over 36,000,000 amperes.

Again an ordinary glow lamp can be maintained at full brilliance even when apparently short circuited by two or three feet of thick copper rod.

Capacity Effects.—Small capacities become as important as small self-inductions. An ordinary Leyden jar appears to act as an almost perfect conductor, though there is no real conduction. The writer has succeeded in lighting a 25 volt ·6 ampere lamp in series with a sheet of $\frac{1}{32}$ in. micanite with coatings of tinfoil about $2\frac{1}{2}$ in. by $2\frac{1}{2}$ in. pasted on either side.

Skin Effect.—In all cases where a changing current flows along a conductor there is a tendency to concentration in the outer layers of the metal. The reason for this is that the magnetic field built up by a current is not confined to the space outside the conductor. Imagine a cylindrical conductor divided into concentric insulated tubes or layers, the smallest of them surrounding a central core, and the largest forming the outermost layer as shown in Fig. 829. Suppose for a moment that only the central core carries current, it is clear that the magnetism formed in rings round it will, to a great extent exist in the space between it and the outside layer, and that during any change in the value of the flux the lines of magnetic force will cut the innermost tube more than the outermost, the latter only being affected by the lines formed outside it in the surrounding insulating medium. During the decay or formation of the field, each layer is cut less than the one within it, and the same holds good if the current be considered to flow solely in any one given layer.

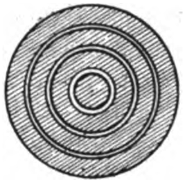


FIG. 829.—DIAGRAM SHOWING PRINCIPLE OF SKIN EFFECT.

It follows that if equal currents were forced through all the tubes the outermost would undergo the least cutting and therefore the self-induction of each layer would be less than that within it.

But if the layers be united to form a solid rod, a changing current being sent through it from end to end, the outer layers, as before, have less choking effect than the central portions; the current is consequently densest at the surface and falls away towards the centre.

The skin effect is very much greater with oscillatory discharges than with currents at ordinary frequencies; it is also affected by the magnetic properties of the conductor, being greatest in iron because the magnetic field becomes very dense in the mass of the metal. In copper conductors of more than ½ in. diameter, the skin effect becomes sufficient to materially decrease the effective sectional area even with ordinary alternating currents.

High frequency currents are almost entirely confined to a surface skin, the depth of which is only a very small fraction of a millimetre. It follows that for oscillatory currents the conductivity of a wire is proportional, not to its sectional area, but to the periphery of its section, and therefore to its diameter if it be cylindrical.

To use material economically for carrying high-frequency currents, it must be made of tube or of thin flat strip, and it is for this reason that broad metallic ribbon is used for lightning conductors.

Induction Effects.—As the induced electromotive force depends upon the rate of change of the flux, it follows that small alterations taking place very rapidly may produce inductive effects as great as those of large fluctuations at a lower frequency.

The author, repeating a well-known experiment, has been able to light a 25-volt lamp across a distance of over 2 feet by induction between two coils of only seven turns each.

OSCILLATION TRANSFORMERS.

Very high voltages are easily produced by transformation of condenser discharges, but the difficulties of insulation are considerable, as most ordinary insulating materials have much too high a dielectric capacity.

High frequency discharges seem actually to "eat" through thicknesses of paraffin wax or ebonite which would be perfect insulators for an ordinary induction-coil spark of the same length, and, unlike the sudden piercing by such a spark, the breakdown which they cause takes place gradually.

The extremely rapid changes of strain in the mass of the insulator result in what is known as dielectric hysteresis; this develops heat (as though there were a kind of electrical molecular friction), and a softening of the insulator ensues. There seems to be a tendency to disperse any loose bubbles or small collections of gas through the material in such a way as to damage it as an insulator.

The only really satisfactory insulator for this purpose is oil. It has a comparatively small dielectric capacity, and is able to circulate if there is any local heating, and to close together naturally if pierced by a spark.

It also has considerable dielectric strength, and all traces of air or other gas among the windings of an oil-insulated oscillation transformer are instantly expelled the first time it is set in action, the insulation being therefore improved with use.

Remarkable effects can be obtained with high-voltage discharges produced by such transformers, but for want of space we must refer the reader to the writings mentioned at the end of this chapter.

Use of Iron Cores.—The use of iron cores, however well laminated, is a positive disadvantage in either choking coils or transformers where oscillatory discharges are concerned. Not only is power wasted by induction of eddy currents in the iron, but the demagnetising force due to these currents reduces the flux, and the loss due to hysteresis is so great as entirely to counteract any improvement in the magnetic properties of the circuit.

Tesla's Work.—Mr. Nikola Tesla, of New York, has carried out most interesting researches on the many interesting phenomena connected with the oscillatory discharge, and, though the briefest summary of his work must suffice here the reader will find full accounts in his lecture before the Institution of Electrical Engineers, Vol. XXI., 1902; also see his book "Experiments with Alternating Currents of High Potential and High Frequency," The W. J. Johnston Co., Ltd., New York; *Elect. Rev.*, New York Vol. XXXIV., 1899, pp. 193-197 and 204; *Nature*, Vol. LXII., 1900, pp. 116-117; *Century Magazine*, June 1, 1900; and *Elect. Engineer*, New York. Vol. XXVI., pp. 477-481. Many of the results already described are due to Mr. Tesla, from whom the high-frequency oscillation transformer receives its popular name, the Tesla coil.

Some of the most interesting experiments were carried out with a view to making a lamp capable of being worked direct by high-frequency high-potential currents.

CHAPTER III.—ELECTRIC WAVES.

ELECTRIC WAVES: MAXWELL'S PREDICTIONS—EARLY EXPERIMENTAL WORK—WORK OF HERTZ—OSCILLATORS—THE OPTICS OF ELECTRIC WAVES.

THE previous chapter leads naturally up to the subject of electric or Hertzian waves, for it is electric oscillations which produce these waves, and they in their turn, travel out into space in all directions, and cannot be detected by any known apparatus without the aid of some receiving conductor which converts their energy back into oscillatory currents and electromotive forces.

By a scarcely avoidable looseness of terminology the various devices which really indicate the presence of wave-induced oscillations, have been called wave detectors, kumascopes, etc. This objection is, perhaps, pedantic, as one may look upon these induced effects as *waves* of E.M.F. and of current. In any case the present writer will content himself with emphasising the fact that all receiving apparatus connected directly with the aerial conductor are really operated by oscillatory currents and E.M.F.s induced in the aerial by the incoming waves.

The term "detector" henceforth means any device for indicating the presence of feeble electric oscillations in a conductor. Seeing that the transfer of energy from transmitter to receiver is by means of electric waves, it is also important to gain a thorough understanding of their properties and production. In the last chapter it was shown that two electrical phenomena must be combined in order that oscillatory discharges shall be produced. If either of these phenomena were eliminated, natural vibrations of electricity could not exist. A similar combination is necessary for the production of true electric waves travelling out into space.

All waves whether of water, sound, or light, travel outwards at definite velocities depending upon the transmitting medium which conveys them, but by reflecting them back towards their source, the returning waves can be made to interfere with the outgoing waves so as to produce what are called nodes and loops, or stationary waves. Concentric stationary waves of great beauty can easily be produced in glass vessels containing water by slightly tapping the table on which they rest; in this case the reflection takes place at the circumference of the vessel. The places of maximum vibration are called loops or ventral segments, and the places of least motion are known as nodes.

It is important to remember that though the *wave travels* outwards from the source of disturbance at a definite rate, the *conveying medium has only a vibratory motion*, so that when the whole disturbance has died away a given portion of the medium will be found to have suffered no permanent change of locality. This fact becomes obvious at once if we watch a piece of cork dancing on the ripples of a pond. It is necessary for the propagation of waves that the maxima of the two effects should be a quarter-period apart. For instance, sound is propagated by alternate compression and rarefaction of the medium, and if either the elasticity or mass of the medium could be eliminated, it would not convey true waves. (The term "mass" is here used in its technical sense.)

If air were elastic but massless it would not convey musical sounds at all, and explosive ones would only travel to a limited distance.

ELECTRIC WAVES : MAXWELL'S PREDICTIONS.

In 1867 James Clerk Maxwell, by physical and mathematical reasoning, predicted the propagation of electric waves during the oscillatory discharge of a condenser. He also predicted the properties of these waves, their reflection, refraction, and polarisation, and foretold their velocity of propagation, which is the same as that of all other known transverse ether waves. In fact, he declared all ether waves to be electromagnetic, the only differences in their behaviour being due to their differing frequencies of vibration.

EARLY EXPERIMENTAL WORK.

Subsequently various experimenters noticed phenomena which were really manifestations of electric waves. Among these was the late Professor Hughes who, in 1879, detected electric waves from self-induction sparks by means of microphonic contacts up to a distance of nearly 500 yards. He was in reality the first user of a coherer (*see* page 851), but in addition he realised something of the true nature of the results which he obtained, asserting that the effects demonstrated by him were due to "aerial electric waves"; he would doubtless have arrived at a most interesting conclusion had he pursued his researches farther.

Dr. Joseph Henry and Professor Silvanus Thompson experimented separately with electric waves at about the same time, and both partially realised the nature of the results they obtained.

THE WORK OF HERTZ.

Professor Hertz in 1888 made the grand discovery which, in the words of Sir Oliver Lodge, "will hand his name down to posterity as the founder of an epoch in experimental physics." A few years after his results were published, he died at the age of 37, intensely regretted not only by the scientific world, but especially by those with whom he came into personal contact. (*See* page 2, "Signalling through Space without Wires," by Sir Oliver Lodge.)

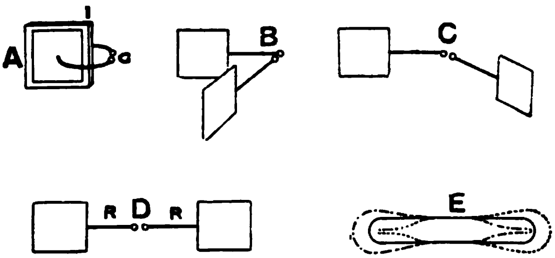


FIG. 830.—DIAGRAMS SHOWING THE PRINCIPLES OF THE HERTZ OSCILLATOR.

So far we have considered only the effects produced by the discharges of ordinary condensers of the Leyden-jar type through circuits possessing the property of self-induction. In certain respects such oscillating circuits are unsuitable as radiators of electric waves, and they must be modified for that purpose for the reasons which follow.

Referring back to the oscillatory discharge circuit described on page 841, the reader will remember that it consists of a pair of conducting surfaces, plane or cylindrical, separated by a sheet of insulating material and provided with a self-inductive discharge path. A rough perspective sketch of such a circuit is given in Fig. 830, where the gap G is shown placed between the ends of a pair of bent rods, the self-induction of the discharge-path being quite sufficient for the production of oscillations.

The true radiation of energy from such an oscillator is insignificant, because it does not give the necessary combination of electrostatic and electromagnetic effects; the former is almost entirely confined to the thin layer of dielectric I which separates the plates, and the latter therefore returns its energy into the circuit at every half swing by a process similar to that by which a moving mass gives up its energy to a spring to which it is attached (*see* page 839).

B represents the same oscillator with the insulating plate I removed, the rods straightened, and the front conducting plate swung outwards. Such an arrangement is still an oscillator, but we have replaced the solid dielectric I by a wide air space.

As air has considerably smaller dielectric capacity than glass, ebonite, etc., and as the space across which the electric stress must act is greatly increased, the capacity is enormously reduced, and the frequency is consequently raised to a high value.

The energy which a given voltage is capable of storing is in this case comparatively insignificant but, what is far more important, the electrostatic lines are freer, and can reach out into the space surrounding the plates sufficiently to enable them to detach themselves in combination with the magnetic whirls round the rods and to travel out as radiated energy; such energy never returns to the circuit, and must continue onward indefinitely unless it meets with some body which reflects or absorbs it.

C is a further stage in the process of opening out of the plates, the final arrangement of which is shown in D, where both plates and rods lie in the same plane.

The capacity is now still smaller and the frequency higher, but the electrostatic field reaches out widely into the surrounding space and distributes itself along lines which leave one plate, curve outwards to some distance, and return to corresponding points on the other plate.

C is a more powerful radiator than B, and D than C, in fact, D radiates so rapidly that only a few swings are completed before the energy has all left the circuit and the oscillations have consequently died away. The arrangement D is, in fact, the oscillator used by Hertz, and it is with this simple apparatus that he carried out his epoch-making experiments.

Hertz found that a gap of about 1 cm. was best, and as the capacity of the arrangement is very small, the energy supplied by an induction coil giving a half-inch spark is ample for exciting the oscillator, each terminal of the coil-secondary being connected to one of the rods R R. Sometimes Hertz employed other forms, but the principles involved were the same.

The detector used by Hertz was a circle of wire or metal rod with a micrometer spark gap introduced at some point in its circumference.

Such a ring, used as shown in Fig. 831, acts as a receiver of the waves, which induce in it oscillations surging backwards and forwards diametrically in a direction parallel to the axis of the rods R. R. These surgings manifest themselves as minute sparks at the gap. The ring was of such dimensions that its natural period of oscillation was the same as that of the vibrator, so that it should resonate

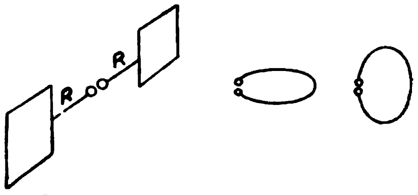


FIG. 831.—THE HERTZ OSCILLATOR AND RESONATOR.

and give better response (*see* page 856), and for this reason Hertz termed the instrument a resonator.

With this detector Hertz explored the space round the oscillator, finding out in what directions the radiation was greatest. By reflecting the waves back upon themselves from a large metallic sheet he produced stationary waves, and proved their presence conclusively.

By experiment and calculation Hertz deduced the velocity of propagation of the waves. The universal law for travelling waves was also found to apply to electric waves. Algebraically it is stated thus: $v = n\lambda$ where v is the velocity of propagation, n the frequency and λ the wave length.

Hertz was able to state with confidence that the velocity of electric waves was identical with that of light; exact experiments have since been made, the frequency being measured by special arrangements for photographing the spark. The velocity has thus been found to be, as nearly as possible, $2{\cdot}991 \times 10^{10}$ cm. per second, or 186,365 miles per second.

Hertz also changed the path of the waves by interposing a huge prism of pitch five or six feet in height and weighing about 12 cwt.

OSCILLATORS.

Other oscillators of various types have been devised since the time of Hertz, and some of the most interesting of these have been designed with a view to decreasing the wave length for experiments on the physics of electric waves. Sir Oliver Lodge, who has done more for the science of electric waves and the art of wireless telegraphy than any other worker since the time of Hertz, carried out important experiments on these lines.

Professor Jagadis Chunder Bose, of Calcutta, constructed an interesting oscillator for his optical experiments. It is like one of Sir Oliver Lodge's oscillators in type, and consists of small discs, between which is a central sphere 1 cm. in diameter. The oscillation-frequency is 30,000,000,000 $\sim$ per second, and the wave length is about 1 cm., but many attempts have been made to produce still shorter waves.

A pair of simple brass rods in line with each other and separated by spark balls forms a good oscillator, and waves that may be detected even at a distance of several yards occur when a minute discharge takes place between an electrophorous plate and a polished brass door knob. The contact spark of an ordinary electric bell is accompanied by oscillatory disturbances which can be detected at a distance of several yards, and this fact is made use of in testing the adjustment of receiving apparatus in wireless telegraphy.

THE "OPTICS" OF ELECTRIC WAVES.

It is now an established fact that all ether wave-motions are electromagnetic in nature, the only difference being in wave-length, and therefore in frequency. The oscillations which produce heat and light waves are molecular in their dimensions, whereas in wireless telegraphy we are concerned with waves which may be several hundred yards in length.

Sir Oliver Lodge repeated, and added to, the pseudo-optical experiments of Hertz with more manageable apparatus, and with a coherer-detector of a far more sensitive type than the Hertz resonator. The comparatively short waves produced by the Lodge oscillator enabled him to reduce the reflectors, prisms, polarising grids, etc., to more convenient dimensions.

A full account of Sir Oliver Lodge's experiments in this and kindred matters with much else of interest will be found in his book, "Signalling through Space without Wires: The Work of Hertz and His Successors."

Professor Bose has produced with Hertzian waves nearly all the effects with which we are familiar in the case of light waves.

The degree of transparency of substances is largely dependent on the frequency of the waves in question. For instance, heat radiation passes easily through ebonite, which is opaque to light. Good conductors always absorb Hertzian radiations, the metals being very highly opaque.

Insulators are comparatively transparent to Hertzian waves unless they are damp, but wood, cloth, earth, bricks, etc., when wet, are highly opaque, and these with semi-opaque substances are capable of acting as partial reflectors ; for instance, Professor Fleming has shown that the human hand can be used as a mirror.

CHAPTER IV.—WIRELESS TELEGRAPHY.

HERTZIAN WAVE TELEGRAPHY—AERIALS—METHODS OF EXCITING AERIALS—SYNTONY—RESISTANCE DAMPING—POTENTIAL AND CURRENT IN AERIAL—DETECTORS—EFFECTS OF NATURAL CONDITIONS—APPARATUS FOR LODGE-MUIRHEAD SYSTEM—MARCONI APPARATUS—VARIOUS DETECTORS.

HISTORY OF WIRELESS TELEGRAPHY.

BROADLY speaking there are three methods by which "signalling across space without connecting wires" has been accomplished; these are the Earth Leakage, the Induction and the Hertzian Wave methods. As the first two have been quite displaced by the third they will not be dealt with here.

HERTZIAN WAVE TELEGRAPHY.

In 1895 Sir Oliver (then Dr.) Lodge detected waves over a distance of about forty yards using a filings-tube coherer and a galvanometer. The coherer, described below under "Detectors," is an imperfect contact, or a number of imperfect contacts, inserted in a circuit containing a cell. These contacts, often formed by dipping two wires into a small pinch of metallic powder, have considerable resistance until the E.M.F. applied to them is suddenly increased, when the resistance falls to a very low value, allowing the current to flow from the cell through any suitable indicator.

In wireless telegraphy, the sudden increase of E.M.F. required to operate the coherer is produced by the induction of oscillations in a conductor when Hertzian waves fall upon it. All ordinary types of coherer remain in this conducting state until they receive a slight mechanical shock; this restores them to their original condition of almost complete insulation.

In 1889 Sir Oliver Lodge, experimenting on the resonance effects of jar discharges, employed a single-contact coherer consisting of two knobs lightly touching each other and inserted in the circuit of a battery and an electric bell. When the bell was mounted on the same base with the knobs, the shock produced by its action automatically restored the coherer to its normal condition.

As early as 1894 automatic clockwork tapping devices were used, and signalling was carried on from a distance through walls by Sir Oliver Lodge.

In the same year Dr. Alexander Muirhead foresaw the telegraphic importance of this method of signalling immediately after hearing Sir Oliver Lodge's lecture on Hertzian waves, and actually arranged a coherer, siphon recorder and automatic tapper for the purpose, obtaining excellent signals. (*See* Sir Oliver Lodge's book, mentioned on p. 849.)

In 1895 Professor A. Popoff, of Cronstadt, Russia, used and described apparatus in which an ordinary lightning conductor was connected to one terminal of a coherer, and the other terminal connected to earth. Across the coherer a cell was connected in series with a relay, the contacts of which closed a second circuit containing a battery and bell; the latter was arranged so that its hammer struck the coherer, acting as a restorer or "tapper." With this apparatus Professor Popoff recorded waves arriving from distant lightning flashes.

In 1895 or 1896 Captain Jackson, R.N., made experiments for the Admiralty and succeeded in telegraphing between ships. (*See* Lodge *loc. cit.*)

In June, 1896, Mr. G. Marconi, who had studied under Professor Righi, of Bologna, took out a patent for "Improvents in Transmitting Electrical Impulses and Signals, and in Apparatus therefor."

In this patent the most important feature seems to have been the insulated vertical conductor connected with one pole or end of a sparking appliance, the other end of which was connected to earth. This was claimed in combination with a receiver of the kind mentioned above. In this receiver the sensitiveness and certainty of action were improved in some respects as a result of experiments, and one or two novel improvements were introduced. *See* the account of the Marconi apparatus given below.

In 1897 Sir Oliver Lodge, who maintained from the very beginning that syntony or resonance was essential to the proper working of wireless telegraphy, took out a number of patents for a system designed and arranged from this point of view, and most workers have since then found it necessary to follow in his steps. Some attention will be devoted to this subject on another page, where it will be shown that the Marconi radiator, used in the manner described in the 1896 patent, is practically incapable of satisfying the conditions necessary for syntonic working.

THE MARCONI AERIAL.

Abandoning, for the present, the historical aspect of the subject, let us consider what is the action of the Marconi type of aerial. In Fig. 830 E (on page 847), the full line represents a long cylinder of rubber filled with a heavy fluid. Being intended to illustrate the manner in which the oscillatory currents and potentials are distributed in the Hertz radiator D, the portions towards the ends must be or thinner or more stretchable rubber than the central part. In this respect they resemble the square plates of D, which have a large capacity compared with the rods R R. If the heavy liquid were set surging to and fro from end to end, the centre would be the place of maximum flow, the highest pressure being exerted at the ends. The dotted line in the figure represents the appearance of the cylinder at the moment of maximum distension to the right, the left-hand end being in a state of collapse. The dot-and-dash line shows the cylinder half a period later with the left-hand end distended, the right-hand end being almost empty.

These lines therefore, roughly represent two phases of the distribution of the pressure in the cylinder, and of the oscillatory potential in D.

Now let the rubber cylinder be considerably lengthened, made of uniform thickness, and placed in a vertical position with its lower end opening into a tank of liquid, as in B, Fig. 832. Imagine the liquid to have mass but no weight, so that complications may not be introduced by its gravitational tendencies.

If the contents of the cylinder be set oscillating vertically, the distension or collapse produced by an upward or downward rush will be at its maximum at the top, as shown by the dotted lines, and will gradually diminish to the bottom, where the pressure cannot be other than that of the tank itself. The maximum flow, on the other hand, will be at the bottom, and will decrease upwards until it is zero at the top.

These are exactly the conditions of the Marconi earthed aerial radiator, and if we were to plot the values of the potential and the current at various points along the wire, they would give respectively curves like those indicated by the dotted lines P and C in diagram A. In fact, earthing the base of the aerial makes it a point of zero potential and the earth corresponds to the tank of water in diagram B.

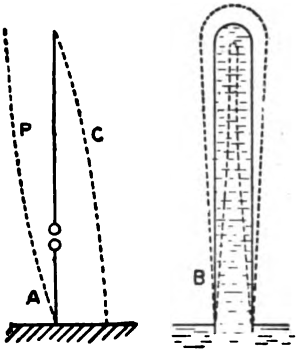


FIG. 832.—DISTRIBUTION OF POTENTIAL AND CURRENT IN AERIAL ILLUSTRATED BY HYDRAULIC ANALOGY.

THE EARTH CONNECTION.

In most of the systems at work at the present day we find that "earthing" is considered essential to satisfactory wireless telegraphy. Failures are stated to be due to bad earths, and we hear of difficulties encountered where the ground is dry.

Emphatic statements to the same effect are usually made in text books and articles on the subject.

Now Sir Oliver Lodge has always consistently maintained that the earth connection is not necessary, and that the ideal transmitter must be symmetrical. Most of his earlier patents describe oscillators as nearly as possible like the original type of insulated symmetrical Hertz radiator. This idea has been carried out in the working of the Lodge-Muirhead system, in which the transmitting and receiving apparatus is connected between upper and lower capacity areas stretched horizontally in such a way as to form a gigantic vertical Hertzian oscillator. *Incidentally*, the lower capacity was in the earlier days earth-connected by laying it on the ground, but it was soon raised on insulating blocks, and as was expected, the excellence of the signalling was improved.

More recent experience has shown conclusively that raising and insulating the lower capacity area three or four feet above the ground increases the efficiency considerably. Carrying this farther, Dr. Muirhead has now carried out quantitative tests which prove conclusively that the best results are obtained when the lower area is at such a height that its capacity is the least possible. If raised above this point its capacity is increased by its proximity to the upper area, and if it is lowered below this point it is increased with regard to the earth. The measured efficiency is 50 per cent. more, and the arrangement makes it possible to tune with extraordinary precision. Mr. C. C. Monckton, in the *Electrician*, Sept. 15, 1905, gives similar experiences.

Professor Fleming, in his Cantor Lectures, mentions reasons for the alleged necessity of earth-connection in long-distance working, and bases his remarks on the theory of bound waves, of which he is so able an exponent.

According to this theory (an account of which will be found in those Lectures), semi-loops of electric strain glide outward from the aerial with their "feet" on the ground, forming bound half-waves. These are never free, but follow the contours of the ground and the curvature of the earth.

This theory accounts satisfactorily for

the fact that wireless telegraphy can be carried on with large portions of the earth's surface intervening between the stations, but the results obtained with insulated lower capacity areas show that the explanation is inadequate, and that other reasons may be adduced for the apparent following of the earth's surface.

The old argument that a network lying near to the earth cannot be better than an earth-connection because it *is* one by virtue of electrostatic induction, is quite untenable in view of the experimental facts given above.

There are two other theories which have been put forward :

(1) That a pair of earthed receiving and transmitting aerials act in reality as the two extremities of a gigantic oscillator, of which the intermediate portion of the earth's surface forms part. If this is so there is actual conduction from the base of one aerial to that of the other.

(2) That free waves are generated, and travel out into space like those from an ordinary oscillator.

The first theory is probably correct for an earthed system, but the recent results obtained with no earth connection, show that in the Lodge-Muirhead arrangement we are concerned with pure radiation and that this is advantageous ; the chief difficulty in the second theory is that there seems to be no thoroughly adequate explanation of the fact that the waves can be received from a distant station when large opaque masses of earth or water intervene. Diffraction and the zig-zag reflection between the upper strata of the air and the earth have both been put forward to account for this.

Possibly the earthed aerial acts by a combination of both principles.

Whatever the finally accepted theory may be, Sir Oliver Lodge's original idea has so far proved correct for long and short distances overland and oversea with various obstacles intervening. The results are particularly striking when we remember that overland work is far more difficult than oversea, and that the Lodge-Muirhead aerials are never very high. (*See* page 870.)

MODERN AERIALS.

A plain vertical wire such as was first used by the Marconi Company is quite unsuitable for long distance working, and makes sharp syntony impossible. Its capacity is very small, and as it radiates very rapidly it is incapable of giving the prolonged wave-trains required for syntonic working; its vibrations more resemble a report or "whip-crack" in acoustics than a sounding tuning-fork. (*See* page 856.)

In most systems the capacity is increased by multiplying the number of aerial wires and bringing them down to a common junction above the transmitting apparatus. Sometimes the wires spread upwards like a fan, sometimes like an inverted cone or pyramid as in Fig. 833, which shows Mr. Marconi's multiple aerial at Poldhu, where a plant capable of generating from 50 to 100 h.p. is installed; the aerial is made up of a large number of bare stranded wires, each of which is 200 feet long, and carefully insulated. The four timber towers which support the structure stand at the corners of a square of 200 feet edge, and are 215 feet in height.

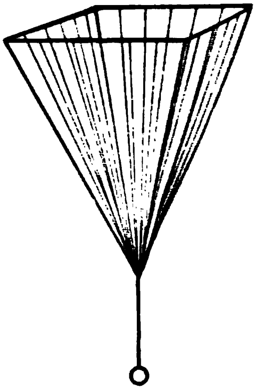


FIG. 833.—MARCONI'S AERIAL AT POLDHU.

With regard to multiple aerials, Professor Fleming (Cantor Lectures) points out that there is great waste of material in placing the constituent wires too closely together, and mentions experiments which prove that if several parallel wires be separated by distances of about 3 per cent. of their length, the total capacity so formed varies roughly as the square root of their number.

He also mentions an interesting aerial of his own design in which the wires are separated sufficiently to avoid this waste, and are made of equal period by adding short coiled lengths to those of them which, by the exigencies of the design, would naturally be short.

None of these arrangements seems to be so satisfactory as the Lodge-Muirhead type described on page 863.

Directive Aerials.—Various workers have recently experimented with aerials arranged for making the radiation stronger in any particular direction which is desirable.

Among the more important of these is one described by Mr. Marconi at the Royal Institution and the Royal Society. It consists of a long horizontal wire stretching outwards from the top of a short aerial in the opposite direction to that in which the signals are to be received. A similar arrangement is used at the receiving station.

METHODS OF EXCITING THE AERIAL.

In Fig. 834 the first diagram (*a*) shows the simple method already described, in which the induction coil or transformer is connected directly across the spark gap, and charges the aerial without the aid of a closed circuit. This method is simple, and has proved effective for the most difficult overland work up to great distances, but where great expenditure of energy is necessary, the arrangement shown in diagram (*c*) is used.

The condenser C discharges through the primary coil P of a step-up oscillation transformer and an adjustable tuning self-induction coil L. The transformer is simply a Tesla coil such as was mentioned in Chapter II., and its secondary S is connected to the aerial A and the earth connection, or lower capacity area. Thus oscillatory surgings are produced in the aerial at higher voltage than could be obtained by direct methods. The natural period of the primary circuit C P L must be identical with that of the aerial A combined with the secondary S.

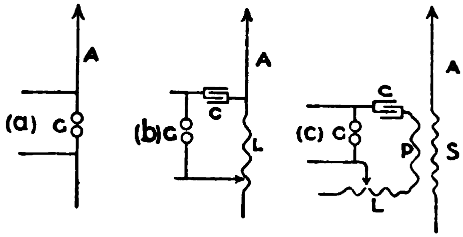


FIG. 834.—METHODS OF EXCITING THE AERIAL.

This arrangement is primarily due to Professor Braun, but, according to Professor Fleming, Mr. Marconi was the first to show that secondary and primary circuits must be tuned together.

A third method shown in diagram (*b*) consists in connecting the base of the aerial to a closed oscillatory circuit at a point where the surging potential is at its highest value. If the closed circuit is in tune with the aerial, the latter acts as a resonator and the potential at the top is far higher than at any point in the closed circuit.

CHARGING ARRANGEMENTS.

In charging the aerials or condensers the points to be considered are as follows:

(1) The voltage and energy supplied by the apparatus must be sufficient to raise the capacity in question to the requisite potential.*

---

* A ten-inch spark coil which generates only a small quantity of electricity in the secondary

(2) The charging must be accomplished quickly, and therefore the resistance of the secondary must be low.

(3) The charges must follow one another rapidly, especially where high speeds of signalling are required.

(4) The charges must be regular in succession and in magnitude.

(5) Economy, convenience of working, durability and portability are obvious considerations.

All these conditions are best satisfied by a special transformer supplied by an alternator.

The insulation between the primary and secondary of the transformer should be very high, especially if an earth connection be used. If it be supplied by an alternator, conditions (2), (3), and (4) are easily satisfied ; so also are the conditions in (5), if the installation is of any magnitude.

For quite small stations, portable accumulators may be preferable from the point of view of economy and convenience.

If a continuous current be used, there must be apparatus for making and breaking it. The ordinary platinum break used with induction-coils satisfies conditions (3) and (4) very inadequately, and shows inefficiency by comparison with other types of break.

For breaking up the primary current into dots and dashes a well insulated Morse key is sufficient for all ordinary purposes, but where great power is used special keys breaking under oil are employed.

Prof. S. P. Thompson patented the use of a choking coil in series with a condenser, with a key normally short-circuiting the condenser, but on depressing the key the short circuit is removed from the capacity, which immediately neutralises the self-induction and allows the current to pass.

Professor Fleming's method is to use choking coils alone and to short circuit one or more of them by means of the signalling key burning in an atmosphere of coal-gas and between the poles of a powerful electromagnet.

CONTINUOUS OSCILLATIONS.

Mr. Valdemar Poulsen, developing certain remarkable results obtained by Mr. Duddell, has succeeded in producing electric oscillations in a continuous stream by means of an unstable arc of special design, in parallel with which is the circuit in which the oscillatory currents are required. The supply voltage is about 400.

With the same object Mr. Marconi and others have been experimenting with different methods. Important and interesting as this work is, the limitations of space absolutely preclude more than a mere mention of it here.

SYNTONY.

Let us return to the weighted spring previously described. We know that by applying a series of small, but properly timed, impulses the vibration can be steadily amplified until its magnitude becomes far greater than that which a forcible single blow would produce.

The process can be carried on indefinitely until the spring snaps, unless there is some retarding action which, at the attainment of a certain amplitude, absorbs energy at the same rate as it is received by the spring.

If we set the spring vibrating at a given amplitude, it would, by similar reasoning, continue vibrating for ever at that amplitude, unless there were a retarding action.

In the case of the weighted spring the retarding action is due to friction, but let

may be insufficient to charge a given capacity to a given potential, while a well-designed six-inch spark coil capable of giving a very heavy discharge may be quite adequate for the same purpose.

us take as an example the tuning fork, the prongs of which vibrate so rapidly that the air, by reason of its inertia, has no time to rush round them and equalise the pressure differences produced by their motion. The periodic compressions and rarefactions of the air travel out into space at regular intervals and fixed speed, forming sound waves. In this case the vibrations decrease in amplitude because their energy is radiated as air waves, and the louder the sound is the more rapidly the energy is dissipated and the sooner the fork comes to rest.

In the case of an electric-wave generator the dissipation of energy is due both to electrical friction—that is, resistance—and to radiation, the latter playing by far the more important part in wireless telegraphy. The rate at which energy is dissipated by an oscillator is known as the rate of damping.

Returning to acoustical instances, let us take the case of a very highly damped vibrator giving only one or two loud impulses when violently struck.

Such a source of sound would easily affect any receiving apparatus which had no natural period of vibration. Thus the drum of the ear or the diaphragm of a telephone would respond well to such a "short, sharp shock," but a heavy tuning fork would give but little response.

A violent report may set a gas-globe singing, but far more effect is produced by a series of much feebler timed impulses which gradually "heap up" the amplitude of its vibration. If the natural note of the gas-globe be sung accurately near to it the added effects of the long wave train from the vocal cords is far greater than that of a pistol shot at an equal distance.

Similarly, if two exactly similar tuning forks be placed close together, one being made to vibrate, the other will resonate, gradually accumulating the small instalments of energy received from each wave until it gets up a considerable swing of its own. On stopping the sounding fork, the resonating fork will be heard to sing the same note.

If one fork be slightly weighted its period will be lengthened, and it will cease to respond because the vibrations set up in it gradually get out of phase with the arriving waves until they are of opposite sign and there is complete neutralisation.

In wireless telegraphy analogous effects are made use of, and the qualities of transmitter and receiver most suitable for obtaining resonance effects are the same as those found necessary in acoustics.

Thus the natural oscillation period must be identical, and the damping must be as small as possible in order that the oscillations set up in either shall not have their energy dissipated rapidly.

The condition of electrical resonance between oscillators has been investigated with great thoroughness by Sir Oliver Lodge, who termed it syntony, and who was the first to realise its very great importance in wireless telegraphy. His historic "syntonic jars" experiment shows his early appreciation of this point, and the reader will find it worth while to examine his account of it in "The Work of Hertz and his Successors."

The mathematical conditions of syntony are expressed by the equation given in the chapters on ordinary alternating currents.

If the frequency of the transmitted waves be n and 2π be called p, then the self-induction and capacity of the receiving apparatus must be such that

$$pL = \frac{1}{pK}$$

One other important point must be considered in this connection.

Let us suppose that we have two springs, one very weak and the other very stiff and strong, and both requiring to be weighted so that their frequency of oscillation shall be the same. The mass attached to the free end of the stronger spring must be greater than that required for the weaker. Similarly, two oscillatory circuits of equal periodicity could be arranged, one with a large capacity and small self-induction, and the other with a small capacity and large self-induction.

The circuit with the large capacity is termed by Professor Fleming a "responsive circuit," because, like the lightly weighted weak spring, vibrations are comparatively easily set up in it by sudden impulses of a non periodic nature. The corresponding description of the other circuit is "stiff," and, like the strong but heavily weighted spring, such a circuit is responsive only to a long train of accurately timed impulses.

Objects of Syntony.—In wireless telegraphy the following three ideal results of good syntony may be emphasised:

(1) Increase of sensitiveness and range of the apparatus.

(2) Selective exclusion of incoming undesirable waves.

(3) Exclusion of other stations from the reception of messages not intended for them.

The art of obtaining fine and accurate syntony has now attained such perfection of working that in some systems it is only by process of careful trial that unfriendly stations can arrive at the wave length sufficiently accurately to interfere, and even this can be prevented by some prearranged system of frequently changed wave length

Where accurate tuning is required, the capacity of the aerial must remain constant, and for this reason balloons and kites have proved impracticable for supporting aerials, because their movement causes continual changes in height.

RESISTANCE DAMPING.

The damping effect of resistance, though less important than that of radiation, is worth consideration, especially as the energy dissipated in this way is wasted as heat. The most important resistance loss is in the spark gap.

Professor Slaby has carried out valuable tests with the object of reducing this loss. For a 120′ air wire of copper 3 mm. thick the damping was found to be about 8 per cent. per period of the energy of the oscillations. Tests made on air gaps showed that with increase of capacity, the resistance per mm. of spark-gap is decreased at all lengths, and that the resistance rises parabolically with the spark length.

Multiple Gaps.—It follows from this fact that short gaps have comparatively more than proportional conductivity, and, therefore, that much will be gained by subdivision. Thus, in a case investigated by Professor Slaby, a 10 mm. gap with a discharge voltage of 30,000 volts, had an effective resistance of 15 ohms, but three gaps in series, each 2·5 mm. in length with the same discharge voltage, had a total resistance of 6 ohms. Multiple spark-gaps are used with great success in more than one system.

THE DISTRIBUTION OF POTENTIAL AND CURRENT IN THE RECEIVING AERIAL, AND ITS EFFECT ON THE USE OF VARIOUS DETECTORS.

In a syntonised earth-connected aerial responding to incoming waves the current and potential are distributed exactly as in the case of the transmitting aerial, the potential rising to a maximum at the top and the current being greatest at the bottom, as shown in Fig. 832.

Now let us suppose that we have two detectors, one depending for its action on the strength of the current passed through it, and the other on the value of the potential difference set up between its terminals.

If the first detector were of fairly low initial resistance it would clearly work best when inserted between the base of the aerial and the earth, where the current is greatest. This, however, is an unsuitable method of connecting a detector which depends on potential difference for its action. The difficulty is not surmounted by placing the detector at the top of the aerial where the potential is high, for it is only high with regard to the earth, and to get the required potential difference a wire cannot be brought down to the earth from the second terminal of the detector; such a wire would act as a receiving aerial and its potential would rise to a maximum at the summit, the distribution being the same as in the original aerial. Thus the detector would be connected between two points of equal potential, an obviously absurd arrangement. Professor Popoff used a detector of this description inserted between the base of the aerial and the earth, a connection which, as we have seen, is only suitable to detectors worked by current.

It is only by overtones or parasitic wavelengths that such an arrangement works at all. The coherer-detectors used by Professor Popoff and Mr. Marconi had considerable capacity, and accordingly they partially maintained the nodal character of the base of the aerial; they probably only acted by failing to do so completely, or because the aerial was not an exact quarter wave length resonator with a natural node at the earth.

Dr. Fleming was the first to emphasise the importance of distinguishing between *current-operated* and *voltage-operated* detectors, and, in the writer's opinion, the best classification is obtained by placing all detectors under one of these headings. We will now proceed to explain how the difficulty of suitably connecting the latter class has been overcome.

METHODS OF CONNECTING VOLTAGE-OPERATED DETECTORS.

The two methods which have been devised for overcoming this difficulty are shown in Fig. 835. In diagram (*a*) the aerial A is shown connected through the primary P of a *step-up* oscillation-transformer, the secondary, S being connected to the detector D.

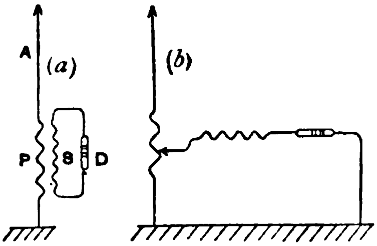


FIG. 835.—METHODS OF CONNECTING VOLTAGE-OPERATED DETECTORS.

Such an arrangement can be made to give a potential difference between the terminals of the detector which is even greater than that existing between the top of the aerial and the earth.

In 1897 Sir Oliver Lodge patented a transformer for use with a voltage-operated detector, and though the receiving apparatus was, in accordance with his original theories, not earth connected, the primary of his oscillation transformer was placed at a potential node where the current was at a maximum, and the secondary was connected in series with the detector, a cell and a current indicator (*see* Fig. 14 of Pat. Spec., 11,575, 1897).

In such an arrangement the transformed oscillations pass through the indicator and cell before they can affect the detector, and as this is very undesirable (whether direct or transformed oscillations are in question) Sir Oliver Lodge, in Patent

No. 18,644, 1897, claimed the use of a condenser as a shunt to a cell and indicator. By this means oscillations have practically a free path by way of the condenser, but the cell can only send its current through the indicator, the transformer secondary, and the detector.

In Patent No. 12,326, 1898, Mr. Marconi made the following claim :—

"Connecting the conductor" (that is the aerial) "to earth through the primary of an induction coil or transformer, and connecting the ends of the imperfect contact" (a particular form of voltage-operated detector) "to the ends of the secondary, one of the connections being through a condenser." Mr. Marconi gives an alternative method of connecting the condenser.

The present writer has inserted the explanatory bracketed portions.

In Professor Fleming's Cantor Lectures, 1903, the following statement is made, after reference to Mr. Marconi's use of the oscillation transformer for receiving :—

"A suggestion to employ transformed oscillations in affecting a coherer had also been made by Sir Oliver Lodge in 1897, but the essence of success in the use of this device is not merely the employment of a transformer, but of a transformer constructed specially to transform electrical oscillations."

A statement so obviously true hardly needs the support afforded by the excellent results which Sir Oliver Lodge and Dr. Muirhead have obtained with their specially constructed transformers.

The second important method of overcoming the difficulty is due to Professor Slaby, who attached a resonator near the base of the aerial and connected the coherer between the end of the resonator and the earth, the difference of potential between these two points being equal to that between the top of the aerial and the earth. The arrangement is shown in Fig. 835 (*b*).

DETECTORS.

For reasons which have already been given, detectors are divided into two broad classes, *Current-operated* and *Voltage-operated.*

This classification is adopted in the tables on the opposite page, in which there is a further division according to the principle of action of the detectors, the columns being occupied by one or two typical examples. The detectors which are indicated by an asterisk are those which are used in wireless telegraphy or which give fair promise of future utility.

It must be remembered that a current-operated detector which has a very high resistance is virtually potential operated, as the current which flows is too small to justify placing it at a potential node. Detectors which tend this way are placed in the current-operated division and are marked with a "†."

Thermal Detectors.—Mr. Gregory, of Cooper's Hill, in the earlier days of electric-wave research used a thermal detector which is described in Sir O. Lodge's "Work of Hertz and his Successors." Professor Fessenden's hot-wire detector is described on page 873. The quantitative thermal detector used by Messrs. Duddell and Taylor in their investigations, consists of an extremely fine resistance, acting as a minute hot-wire ammeter, and arranged in close proximity to a thermal junction which is actuated by its radiations. Professor Boys and others have used thermo-electric junctions direct.

Dr. Fleming's thermal detector is mentioned on page 874.

Electrolytic Detectors.—*See* pages 872 and 873.

Magnetic Detectors.—Hertz and others have used detectors depending directly upon the magnetic effects produced by electric oscillations.

Professor Rutherford, Professor Ewing,

TABLE OF CURRENT-OPERATED DETECTORS OF HERTZIAN OSCILLATIONS.

THERMAL.				ELECTROLYTIC.	MAGNETIC.	
MECHANICAL.	BOLOMETRIC.*	THERMO-ELECTRIC.	IONIC.	—	MECHANICAL.	HYSTERETIC.
Expansion of platinum wire. (*Gregory.*)	Alteration of resistance with temperature. Platinum loop and liquid† barreter with pierced diaphragm. (*Fessenden.*)	Dissimilar junctions. (*Boys.*) Thermal junction actuated by hot wire.* (*Duddell and Taylor.*)	Carbon rectifier:—Lamp filament surrounded by metal cylinder. (*Fleming.*)*†	Rupture of electrolytic trees.* Anti-coherer. (*Neugschwender.*) Electrolytic detectors.* *Schloemilch* ? †. Electrolytic detector.* (*Hozier-Brown.*) †	*Hertz.* Silver ring set at 45° to a coil. (*Fessenden.*)	*Rutherford.* *Ewing.* *Marconi.**

TABLE OF DETECTORS OPERATED BY POTENTIAL DIFFERENCE.

ELECTRO-STATIC OR MECHANICAL.	DISRUPTIVE BREAKDOWN OF DIELECTRICS.			CONTACT EFFECTS. COHERERS.	
ELECTROSTATIC ATTRACTION.	DIRECT DISCHARGES.	TRIGGER DISCHARGES.	DISRUPTION OF POLARISATION FILM. (?)	SELF-RESTORING COHERERS.	NON-SELF-RESTORING COHERERS.
Hertz. *Bjerknes.* *Toepler.* *Boys.*	Spark gap. (*Hertz.*) Spark gap and telephone.	Spark gap and electroscope. Initial voltage from dry pile. (*Boltzmann.*) Vacuum tube. Initial voltage from battery. (*Zhender and Righi.*) Arc between carbon rods. Initial voltage from supply mains. (*Lodge.*)	Platinum wire dipping into electrolyte.* ? (*Fessenden, Schloemilch.*) Note.—It is not quite clear what the action of this detector is.	Ordinary microphones. (*Hughes.*) Carbon-steel contacts.* Carbon-mercury and steel-mercury contacts.* (*Castelli.*) Moving steel-mercury contacts with oil film.* (*Lodge and Muirhead.*)	Simple imperfect contacts.* (*Lodge, Branly, and others.*) Filings coherers. (*Branly, Lodge, Marconi and others.*)* Note.—Scientifically considered, the Lodge-Muirhead wheel coherer should be in this column, but practically considered, it is self-restoring.

Mr. Marconi, and others have devised detectors in which the demagnetising effect of oscillatory currents is made use of. (*See* page 871.)

Electrostatic Detectors.—These detectors are all really sensitive electrostatic voltmeters. An account of the Bjerknes detector—"a one-sided electrometer"—is given by Sir Oliver Lodge ("Work of Hertz," pages 15-16). Others have used suspended wires hung close to earth-connected conductors.

Direct Disruptive Detectors.—Hertz's original resonator is provided with a simple spark gap in which a visible disruptive discharge takes place.

Various methods of making the spark more obvious have been devised.

"Trigger" detectors are those in which an initial voltage is applied to a disruptive indicator, but is insufficient to operate it until it is aided by the added electromotive force of wave-induced oscillations. Most types of coherer, partake of this "trigger" action, but they are best considered separately.

Sir Oliver Lodge struck an arc at a distance by causing the electric waves to give the additional voltage necessary to jump a very small gap between the carbons.

Professor Boltzmann's detector consists of an arrangement in which a high-voltage dry pile is similarly helped to spark across a small micrometer gap into an electroscope.

"*Microphonic*" *Detectors.*—This important class of detectors comprises a large number of distinct forms, all depending for their action upon the variations in the resistance of imperfect contacts under the influence of electric oscillations, and all known as *coherers* (the word is Sir Oliver Lodge's). With few exceptions the effect of the oscillations is to produce a decrease in the contact resistance, and in the majority of cases the detectors do not recover their highly resisting condition until they receive a slight mechanical shock.

Self-restoring Coherers.—A few coherer-detectors are self-restoring, that is, they instantly return to their normal condition on the cessation of the waves, and require no "decohering" device.

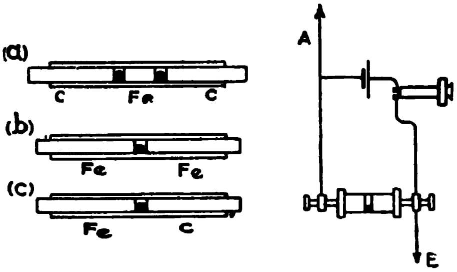


FIG. 836.—CASTELLI COHERER AND ITS CIRCUIT.

The simplest form of self-restoring coherer is made by resting one or more steel needles in light contact with a carbon block or so as to form a bridge between two carbon blocks. The resistance variations of such devices are best made evident by means of a telephone and cell connected in series with them. Each spark is heard as a distinct click in the telephone, so that a dash is rendered as a long buzz and a dot as a short crackle. Very similar is the sound heard if a "Castelli" coherer be substituted for the carbon block arrangement. This coherer has been the subject of bitter controversy, the credit for its invention having been variously assigned to two or three different persons. The numerous articles and letters in the technical Press and elsewhere, which leave a most unsavoury impression on the mind, cannot be dealt with here. The instrument takes three forms which, however, do not differ in their essentials. Fig. 836 (*a*) shows the original pattern, which consists of a glass tube containing a central plug of iron with two carbon plugs on each side and small gaps intervening. These gaps contain globules of mercury from 1½ to 3 mm. in diameter. The plugs are provided with screw adjustments. The detector is inserted in the circuit of a cell and telephone, as shown in the diagram.

Diagrams (*b*) and (*c*) show two other forms of this detector. An interesting and valuable article on this subject appeared in the *Electrical Review*, Vol. LI., page 967. These coherers are rather uncertain in action, and though fairly sensitive, can hardly compete with more recent detectors.

The Lodge-Muirhead wheel coherer, the decoherence of which is simply effected by a continuous change of the point of imperfect contact, only needs to be geared to the clockwork of the syphon recorder used in connection with it. This coherer so nearly approaches to a self-restoring device that it has been classed with other self-restoring types, to most of which it is superior in sensitiveness and reliability.

An important single-point coherer used in the Lodge-Muirhead system is described briefly on page 866.

Non Self-restoring Coherers.—In 1870 Mr. S. A. Varley noticed a coherer effect in carbon and other powders.

Other experimenters were Professor Hughes, 1879; Professor Calzecchi Onesti, 1884–5; Sir Oliver Lodge, 1889 and 1894; Professor Minchin, 1890–1; Professor Branly, 1891; Professor Popoff, 1895; and Mr. Marconi, 1896. For further details *see* Sir Oliver Lodge's "Work of Hertz," etc.

Action of Coherers.—There is no doubt that electrostatic attraction plays an important part in the action of coherers, and doubtless, there is also a kind of welding effect, as suggested by Sir Oliver Lodge.

Professors Branly and Tommasina and Dr. Erskine Murray have all contributed to the investigation of this question, but space will not permit an account of their experiments.

EFFECT OF NATURAL CONDITIONS ON WIRELESS TELEGRAPHY.

Captain Jackson, R.N., F.R.S., having made important tests on a large scale, was able to estimate the ratio of wave-transmission through several rock substances, with the following result:—Soft substance shale, etc., 72 per cent.; hard limestone, 58 per cent.; iron ores, 32 per cent.

Captain Jackson also made exhaustive tests to find out the effect of variations in barometric pressure, of mist and dust-laden air, and of various electric atmospheric conditions.

An electric state of the atmosphere usually tends to diminish the transmitted effect, though in one case it led to a momentary increase of 50 per cent. Professor Slaby says that the best signalling is obtained immediately after a storm.

In long-distance working the signalling is always far more satisfactory during the night, though Messrs. Duddell and Taylor have shown that for short distances the difference is only equal to about 1 per cent. This point is discussed in Professor Fleming's Cantor Lectures of 1903 and elsewhere.

Lightning discharges are often recorded by wireless telegraph apparatus, and there is occasionally trouble through the accumulation of small charges in the aerial. These produce coherence effects which may prove disturbing, but an oscillation transformer passes them away to earth without producing much effect. In the Lodge-Muirhead system they are even more completely eliminated by the use of the lower insulated capacity-area. Much very important information on these and other points is given in Messrs. Duddell and Taylor's paper, Institution of Electrical Engineeers, Vol. XXXV., No. 174.

APPARATUS FOR WIRELESS TELEGRAPHY.

THE LODGE-MUIRHEAD SYSTEM.

Aerials.—As has been already explained, (*see* page 853) an earth connection is definitely avoided in this system, and the lower capacity area is actually raised to a point where its capacity is least, and is formed of a network of the same design as the aerial network. The capacity area now used is in the form of a Maltese cross and gives remarkably symmetrical distribution with almost negligible overtones in the oscillations. Fig. 837 is a diagrammatic representation of the aerial and shows the best height 18 feet) for an aerial 60 feet high.

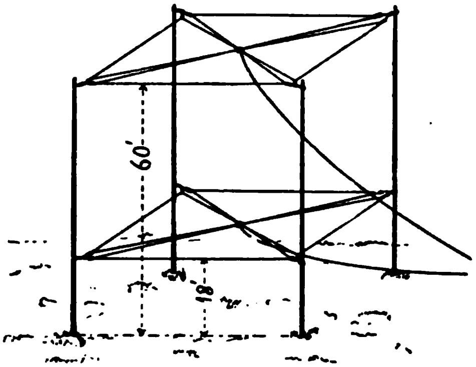


FIG. 837.—LODGE-MUIRHEAD AERIAL.

All the Lodge-Muirhead networks are composed of bare stranded tinned copper wire 7/20, four of these being brought down from the centre for the vertical leading-in wire.

The poles and guy-ropes are separated from the network by hooded porcelain insulators

THE SENDING CIRCUIT.

Fig. 838 shows the connections of the standard sending circuit. D is an alternator giving 200 cycles per second, V is a voltmeter, C an amperemeter, L_1 and L_2 are adjustable choking coils, and P is the primary of the induction coil. The primary circuit is controlled by the switch F and the signalling key K. The armature G of a small continuous-current dynamo excites the alternator D and its own field coils through the variable resistances R_1 and R_2. The secondary S of the coil is connected to the upper capacity area through H which is part of the switch for changing over from transmission to reception; the other terminal of the secondary is connected through the tuning impedance coil L_3 to the lower capacity area A_2. The discharge takes place through the multiple gap M.

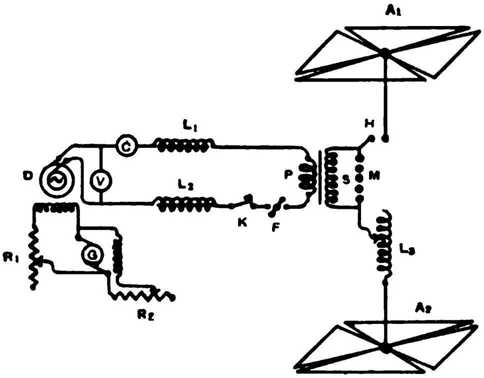


FIG. 838.—LODGE-MUIRHEAD TRANSMITTING CIRCUIT.

Sometimes a Leyden-jar or cased-in ebonite condenser is inserted between the upper spark rod and the vertical wire to prevent short circuiting of the spark coil by leakage from the aerial.

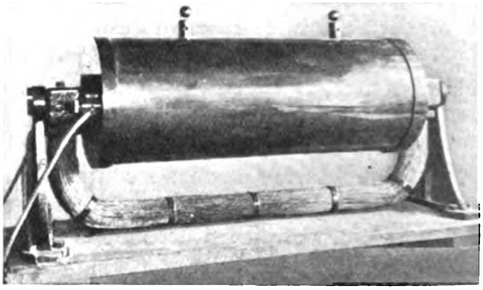


FIG. 839.—LODGE-MUIRHEAD INDUCTION COIL.

A feature of the Lodge-Muirhead system is the perforator and auto-transmitter arrangement long known in ordinary telegraphy.

The induction coil, shown in Fig. 839, has a larger primary and a rather thicker secondary than is usual, and its magnetic circuit can be closed by a yoke of iron wire. It is not suited for ordinary use as an induction coil, and only gives a spark about 8 in. in length.

The coil is actuated by the twelve pole alternator shown in Fig. 840. This is very light and compact, and is mounted on the same bed-plate with its exciter.

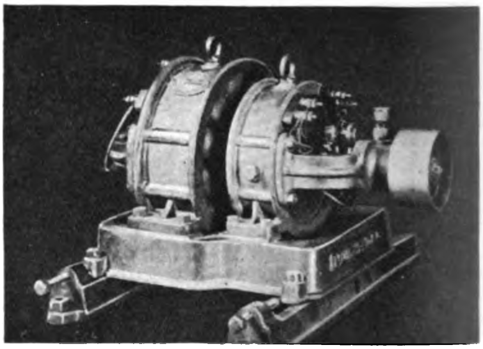
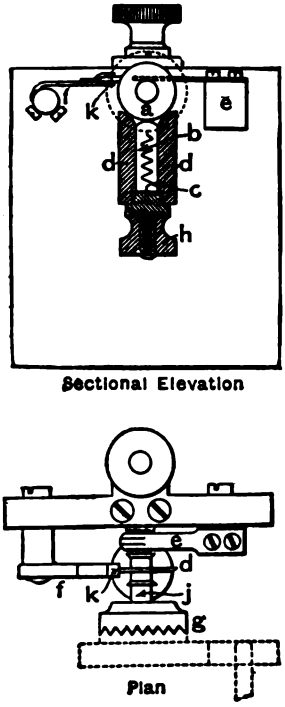


FIG. 840.—LODGE-MUIRHEAD ATERNATOR AND EXCITER.

A regulating switchboard with adjustable choking-coils is provided. The signals are sent by depressing a Morse key, fitted with an extra-long press knob of ebonite. No trouble is experienced in breaking the current with this key.



Sectional Elevation

Plan

FIG. 841.—LODGE-MUIRHEAD WHEEL COHERER.

The sensitiveness and certainty of action of the Lodge-Muirhead System are such that the open sending circuit has been found quite adequate for signalling to the greatest distances. (*See* page 855.)

The Spark Gap.—The spark gap is multiple, that is, it consists of several gaps in series. Where larger powers are used, the small sparking surfaces project diametrically opposite to each other from hollow spheres which are filled with water. This keeps the surfaces cool and greatly increases the regularity of working.

THE RECEIVING APPARATUS.

The coherers used in the Lodge-Muirhead receiving apparatus are important features of the system, and are remarkable for their sensitiveness, simplicity and great reliability. The construction of the steel-wheel form is shown in Figs. 841 and 842.

A small steel disc *a* with a fine knife edge, is mounted on a shaft which carries a driving wheel *g* of ebonite. This engages with a brass wheel attached to the shaft of one of the gear wheels of the tape-machine clockwork. Thus the wheel continuously rotates at a speed of about half a revolution per second. The ebonite tube *d* is filled with mercury *b* and is raised by means of the milled-head screw at the top of the coherer, until the edge of the wheel just touches the rounded surface of the mercury; a small quantity of special oil is dropped on the edge of the wheel, thus forming a very thin film between it and the mercury. Too much oil tends to make the coherer insensitive; when there is too little the signals run into one another.

A copper brush *e*, mounted on an insulating block, presses lightly on the shaft and forms one terminal, the other being the screw *h*, to which an amalgamated plat-

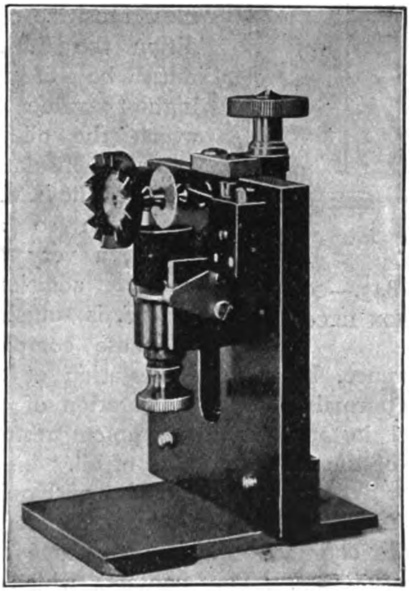


FIG. 842.—LODGE-MUIRHEAD WHEEL COHERER.

inum-wire spiral *c* is attached, so that a really satisfactory contact is established with the column of mercury. A spring *f* carries a small pad of felt *k* which keeps the wheel clean and free from clogged oil. On applying a variable source of E.M.F. so that the steel disc is positive, it is found that as the E.M.F. is gradually raised from 0 to 1, a point is reached at which the film of oil breaks down, allowing a current to flow through whatever detector is placed in the circuit. The actual value of the E.M.F. required to break down the coherer is less than ·5 volts; to get the coherer into its most sensitive condition the E.M.F. must be of the highest value at which the oil-film acts as an insulator.

When the E.M.F. has been so adjusted, a very minute additional E.M.F. is sufficient to cause complete coherence, but on the cessation of the supernormal E.M.F. the rotation of the wheel instantly causes complete restoration of the insulating film of oil.

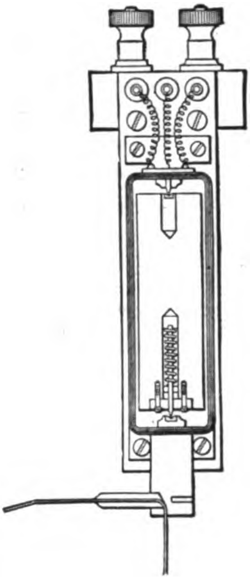


FIG. 843.—COIL OF SIPHON RECORDER.

For light, portable apparatus with quick adjustment, a new single-point coherer is used in conjunction with a telephone and potentiometer. The contact, which is between a blunt steel point and a small carbon block, is immersed in oil. The sensitiveness is adjusted by varying the height of the column of oil.

The Potential-Divider and Siphon-Recorder.—To produce the necessary variable E.M.F., a potential-divider (sometimes loosely called a potentiometer) is employed. This is fed by one accumulator cell and arranged to step up by small amounts to about ·5 volts; its resistance is sub-divided among a number of studs arranged in a circle, a radial contact arm being moved over them by a milled head of ebonite. In the case of the wheel coherer the dot-and-dash variations in the current actuate a low-resistance siphon recorder, and are accurately transferred by it to the tape, which shows every character of the arriving impulses and exhibits any defect in the signalling. This recording of the signals precisely as they are emitted is most useful, and the coherer is so definite and reliable that defects in the record may generally be sought for at the sending end.

The principle of the siphon recorder is that of the D'Arsonval galvanometer. The current is conveyed by one of the three small spirals of wire, seen in Fig. 843, which is a diagram of the coil portion.

The movements of the coil are recorded on the tape by a fine bent glass tube which is fastened in position by a little wax. One end of this tube dips into a reservoir of red ink, and the other rests lightly on the tape, being ground to a horizontal edge to meet it. There are arrangements for adjusting the pressure of the tube on the tape, and the angle and height of the platform on which the tape slides as it passes under the siphon.

The Calling-up Bell.—The third of the wires leading to R (Fig. 844), the moving portion of the recorder, is joined to a platinum contact, which completes the circuit of a bell H when the recorder is first deflected. A lever is provided for withdrawing the contact when the bell has rung, and the operator is ready to receive.

Arrangement of Receiving Circuit.—Fig. 844 is a diagram of the receiving circuit generally used in the Lodge-Muirhead system.

The change-over switch S is shown in the "send" position, where it is held by a spring, the terminals O, being introduced between the primary T_1 of the oscillation-transformer and the point where contact is made with the impedance coil L. The connection is interrupted by the long-break switch B during sending, for if the primary T_1 is left attached to the active aerial, it acts as a resonator, and is liable to form brush discharges at the point V.

The terminals, W R (wave recorder), are in *parallel* with the coherer C, and those marked P are in *series* with the battery D and the potential divider.

Thus, in the send position, where the pair W R is bridged, those at P being isolated, the primary is disconnected, the potential divider is switched off, and the coherer is short circuited, which protects it from disturbances during transmission.

For receiving, the switch-arm E is turned in a clockwise direction, so that it is vertically above the hole in the drilled metal stud V, and a metal plug A, connected with the aerial wire by a flexible conductor, is thrust through the hole in the switch-arm into the plug hole V, thereby securing

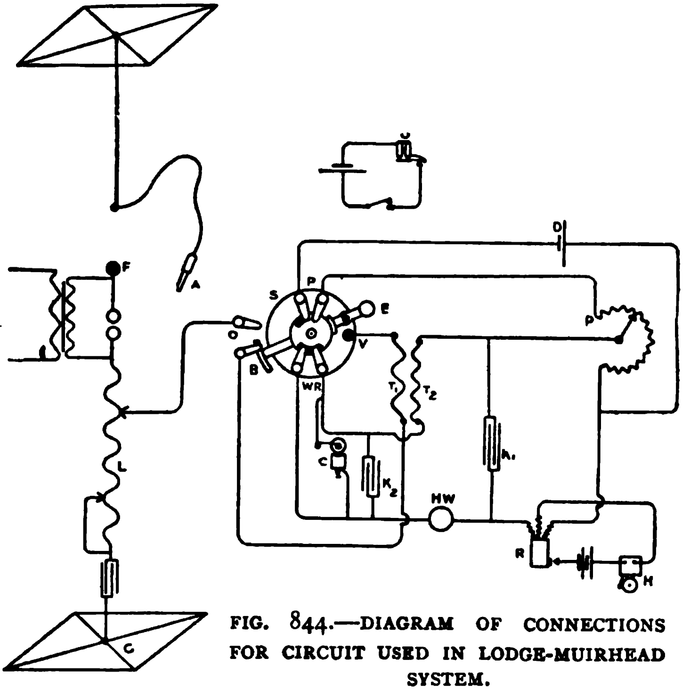


FIG. 844.—DIAGRAM OF CONNECTIONS FOR CIRCUIT USED IN LODGE-MUIRHEAD SYSTEM.

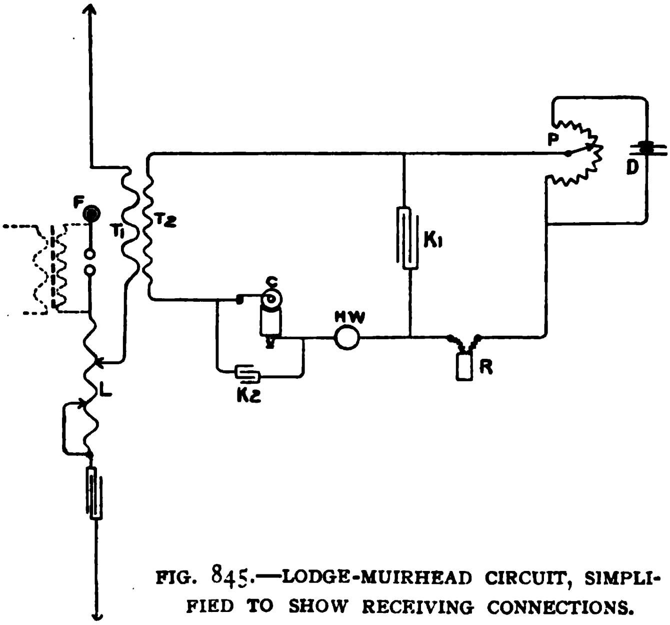


FIG. 845.—LODGE-MUIRHEAD CIRCUIT, SIMPLIFIED TO SHOW RECEIVING CONNECTIONS.

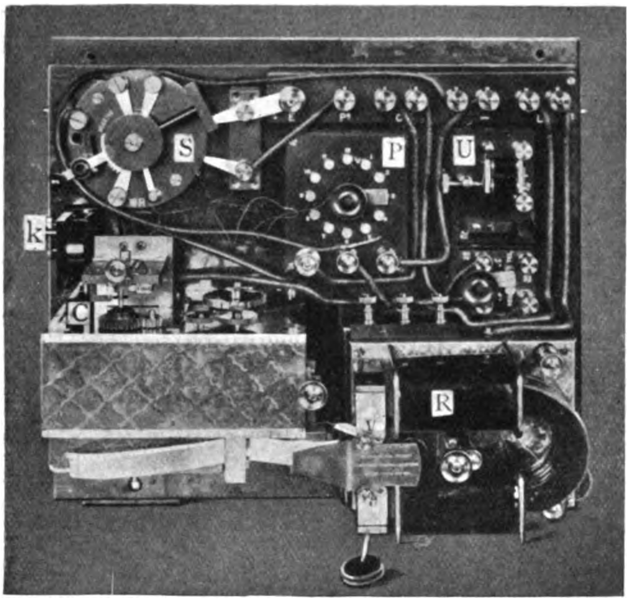


FIG. 846.—COMPLETE LODGE-MUIRHEAD RECEIVER (FROM ABOVE).

the switch in the "receive" position; at the same time it makes connection between the aerial and the primary T_1 of the oscillation transformer. For sending, the plug A is inserted in the hole F connected with the top ball of the spark gap.

In the receiving position the long-break switch B bridges the terminals O so that the primary is connected with the lower capacity area; also the potential-divider circuit is completed, and the coherer is no longer short circuited. The circuit as it now stands is shown in the simplified diagram, Fig. 845.

The aerial with the transformer primary T_1 and any other adjustable arrangements which may be required, are tuned to the frequency of the incoming waves, so that the oscillatory current in T_2 is as large as possible.

After transformation the impulses actuate the coherer C through the capacity K_1, which allows them a free path regardless of the rest of the circuit.

The coherer circuit (comprising the transformer secondary T_2, the capacity K_1 and the combined capacity of the coherer and the adjustable condenser K_2) is also accurately tuned. The film of oil between the wheel and the mercury has a small but definite capacity, which is not subject to the disturbing variations which render tuning difficult with filings tubes. Figs. 846 and 847, which are photographs of the complete receiving apparatus, show the adjustable air-condenser here marked K; this is connected in parallel with the coherer. It consists of two parallel fixed semi-circular plates, and a third plate attached to a milled head so that it can be inserted more or less between them.

The capacities are indicated by a pointer

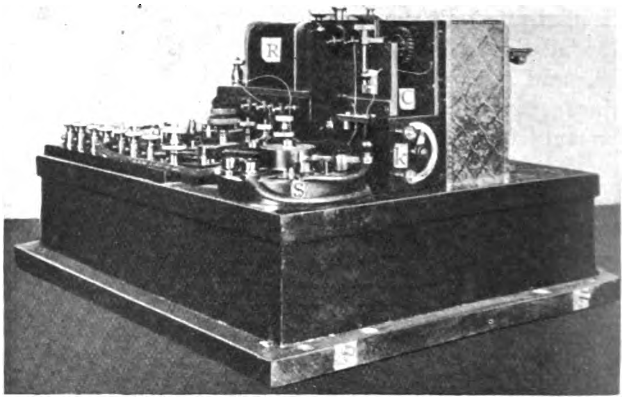


FIG. 847.—COMPLETE LODGE-MUIRHEAD RECEIVER.

fixed to the milled head and travelling over a divided scale. When the added resonance effect of succeeding oscillations has broken down the film of oil, the potentiometer sends its current through T_2 and the recorder R.

In Figs. 846 and 847 the lettering of the different parts has been made the same as in Figs. 844 and 845.

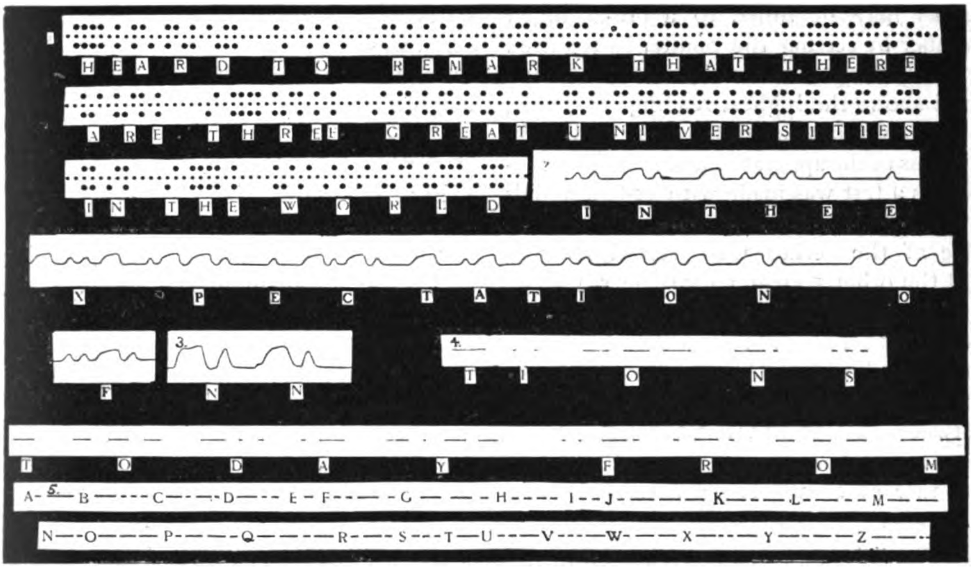

1
H E A R D T O R E M A R K T H A T T H E R E
A R E T H R E E G R E A T U N I V E R S I T I E S
I N T H E W O R L D
I N T H E
N P E C T A T I O N O
F
3
N N
4
T I O N S
T O D A Y F R O M
5
A B C D E F G H I J K L M
N O P Q R S T U V W X Y Z

FIG. 848.—SPECIMENS OF TAPES USED IN LODGE-MUIRHEAD SYSTEM, WITH MORSE-CODE KEY.

The receiving transformers consist of a few turns each for primary and secondary. The tuning and the sensitiveness are so good that for the sake of sharp selective syntony it is possible to place the primary and secondary eight or nine inches apart.

In Figs. 844 and 846 U is a small electromagnet with vibrating armature and contact. In series with a press key and a single dry cell it forms an entirely separate circuit, and is used to generate feeble electric waves for testing the receiving circuit.

Fig. 848 is from a photograph of three specimens of tape, No. 1 being a perforated message ready for the auto-transmitter; Nos. 2 and 3 are good average specimens of messages received in the ordinary working of the system.

No. 4 is rather interesting, being a message received by means of a Lodge-Muirhead wheel coherer used in conjunction with a relay and inker. No. 5 is a key.

TUNING APPARATUS.

For syntonising the aerial to any definite "tune" a single turn of stout copper wire of standardised dimensions is inserted near the bottom of the aerial. At a short distance from it a secondary coil of a few turns of wire is placed, the two forming a simple oscillation-transformer. The coils are placed far enough apart to prevent mutual induction from seriously affecting the frequency.

The secondary coil, a hot-wire current indicator and an adjustable air condenser are connected in series and form a separate local oscillating circuit.

The air condenser consists of a number of fixed brass plates, between which other movable plates can be inserted to a variable extent by means of a milled head projecting from the top of the instrument. A pointer is attached to the milled head and travels over an accurately graduated scale, each figure on which represents a tune number. If each station be provided with duplicates of the apparatus, all the aerials may be tuned to a pre-arranged number by setting the pointer as required and adjusting the circuits until the indicator shows the highest reading.

To ascertain the practicability and sensitiveness of the apparatus under adverse conditions a test was made with 42-foot aerials erected at opposite sides of a mountain. One of the aerials was erected 100 feet and the other 50 feet above the sea level, the horizontal distance through the mountain was 19 miles, and the distance between each aerial and the base of the mountain was a quarter of a mile. The highest ground between the aerials was 3,200 feet. Communication was successfully carried on at the rate of 28 words per minute, though far higher speeds are attainable.

The waggons specially designed to carry the apparatus were taken over the worst possible ground and run into ditches at full gallop without injury to the apparatus, though portions of the woodwork were torn away. The receiving apparatus has also been successfully operated in the guard's van of an express train travelling sixty miles per hour.

The system has now been at work for some years between Rangoon, in Burmah, and Port Blair, in the Andaman Islands, a distance of 3,000 miles, with a power of *400 watts* only.

There is also an installation used by the Midland Railway Company for working between Heysham Harbour and the Isle of Man. This is now extended to Belfast and Londonderry, a large part of the distance being overland. The power is only 400 watts and the working is perfect.

The tuning of the system is so perfect that signalling has been carried on from Elmers End to Hythe, a distance of 60 miles over chalk hills, while a much more powerful station only a few miles distant was, by arrangement, doing its best to disturb the communication.

The Elmers End station worked at 500 watts with a 62 feet aerial, the Hythe aerial was 80 feet in height and the Dover aerial was 180 feet in height.

MARCONI APPARATUS.

Fig. 849 shows the connection of the transmitting apparatus at Poldhu. The high alternating voltage at terminals T T charges the batteries of condensers C C; and these discharge through the primary P of an oscillation transformer, the secondary being connected with the aerial through the tuning self-induction coil L.

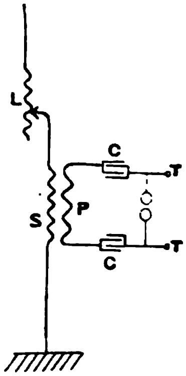


FIG. 849.—CONNECTIONS OF TRANSMITTING APPARATUS AT POLDHU.

RECEIVING APPARATUS.

The receiving apparatus used with the filings-tube coherer is shown diagrammatically in Fig. 850. The oscillatory currents induced in the aerial A pass through the primary P of the oscillation transformer and the variable self-induction L to earth.

The secondary S S is connected to the coherer C which forms part of a second circuit containing the cell B. The secondary is cut in the middle and the condenser K_1 introduced to prevent the cell from short circuiting through it. This condenser is an insulator to continuous currents, but passes the high-frequency surgings induced in S. The choking coils I, I are introduced between the oscillatory and the continuous-current circuits of the coherer to prevent the high-frequency current from dissipation in the latter. The capacity K2 is for tuning purposes.

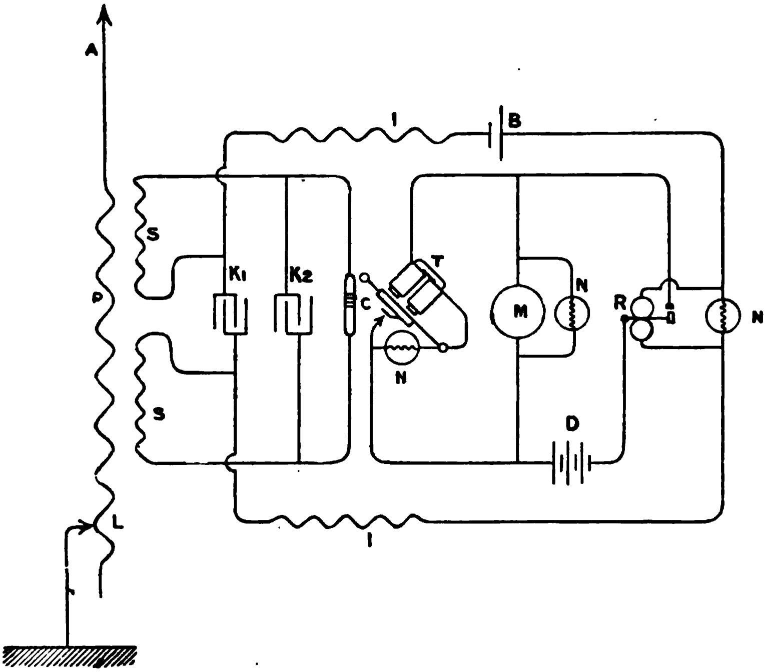


FIG. 850.—DIAGRAM OF CONNECTIONS FOR FILINGS-TUBE RECEIVER.

When coherence is established by the arrival of a wave, the cell B sends a current through C and the coils of the relay R, but can send no current through S S because of the condenser K.

The Relay.—The relay used is of the Siemens polarised type, and has a resistance of from 1,200 to 10,000 ohms; it is extremely sensitive. Its contact closes the circuit of the battery D which sends current through the tape-instrument or sounder M and the decohering tapper T. The message is delivered in dots and dashes by M.

The Tapper.—The tapper T works on the same principle as an electric bell, the hammer being arranged by various adjustments to give the coherer the most suitable kind of shaking for decoherence.

The Coherer.—A recent form of Marconi coherer (shown in Fig. 851) consists of a glass tube about $\frac{1}{8}$ in. internal diameter, furnished with silver plugs, the ends of which are shaped off at a slight angle. In the gap are placed metallic filings, carefully sifted to a definite size; 95 per cent. of the filings are of nickel and the rest of silver. The V shape of the gap is for varying the sensitiveness by rotating the tube. Connections are made by the platinum wires sealed in at the ends, and the tube is exhausted to prevent the surfaces of the plugs and filings from oxidising.

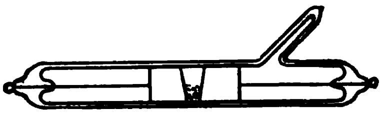


FIG. 851.—MARCONI COHERER.

Non-inductive Shunts.—To prevent the coherence caused by self-induction sparks at the various contacts, non-inductive shunts N N are provided; these absorb quietly all surgings and kicks which would otherwise keep the coherer in a continually conductive state.

The Magnetic Detector.—The effects of electric sparks on magnetised steel noticed by Professor Joseph Henry, of the United States, about the year 1830, became in 1896 the subject of a series of systematic experiments by Mr. Rutherford, who found that feeble oscillatory currents could demagnetise iron wires placed inside a coil. The effect is similar to that which is made use of for the demagnetisation of watches, which are placed in a rapidly alternating field and are then gradually moved to a distance. The initial magnetisation is reversed and raised to a slightly lower value, and each alternation of the current produces a reversed but feebler flux in the watch until when sufficiently far off it ceases to be magnetised at all.

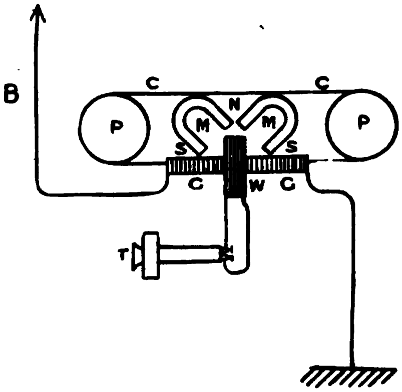


FIG. 852.—MARCONI'S MAGNETIC DETECTOR.

When demagnetisation is effected by the oscillatory current, the gradual weakening produced by removing the watch is replaced by the natural decay of the surgings in the coil.

The instrument adopted by Mr. Marconi is shown in Fig. 852, where two magnets M M are represented with like poles placed together so as to magnetise the endless band of stranded iron wire C; this continually moves through the coil G, being carried round by the pulleys P P, one of which rotates by clockwork. The hysteresis lag causes the field to be carried on by the wire a little beyond the central point, and when oscillatory currents flow through G the residual lagging flux is annulled, and the magnetism may be said to jump back to the central position. This slight though rapid shifting of flux induces a current in the coil W so that a click is heard for each spark transmitted. Thus a dot is rendered by a short crackle, and a dash by a long buzz. The sounds are not very loud, but the action is regular.

This is a current-operated device, and can be inserted directly between the aerial and earth.

DE FOREST APPARATUS.

The principle of all Dr. de Forest's early detectors seems to have been identical with that of Neugschwender's "anti-coherer," which is made as follows:

A cut about ·3 mm. wide is made across the coating of a silver-on-glass mirror, and a slight deposit of moisture is made to condense in the gap, by breathing upon it or placing a scrap of wet cloth near to it. The effect of a wave is to cause a momentary rise of resistance which produces a click in a telephone connected in series with the detector and a cell. The increase of resistance almost amounts to a complete interruption of the current, but the detector is self-restoring, and the return to a conducting state is practically instantaneous. A similar instrument has been invented by Schäfer, in Germany. In the gap the current builds up crystalline bridges of metallic silver which have a fairly low resistance. The oscillatory currents induced by received waves break up and scatter these electrolytic trees, causing a momentary increase of resistance which is made evident by a click in the telephone.

Most interesting observations and experiments in this connection may be found in an article by Dr. de Forest in the *Electrician* of November 4, 1904.

In the course of his attempts to utilise this principle in a more reliable way, Dr. de Forest has tried various mediums and depolarising agents with varying degrees of success; accounts will be found in the above-mentioned article and elsewhere.

LATER ELECTROLYTIC DETECTORS.

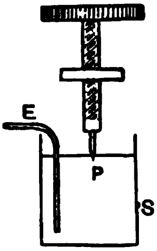


FIG. 853.—ELECTROLYTIC DETECTOR.

A later type of electrolytic detector used in various systems is shown in Fig. 853. It consists simply of a very fine platinum point, with a screw adjustment and a small vessel containing an electrolyte into which the platinum point P dips, a metal plate or wire E of much larger dimensions being immersed in the liquid to act as a second electrode. The action of electric waves is to produce an alteration of resistance, the reasons for which have been much discussed. By a series of interesting experiments (*see* the *Electrician* of November 4, 1904), Dr. de Forest seems to have established the following facts:

(1) That the detector is not a heat-operated device.

(2) That its action is not destroyed by extremes of temperature, high or low.

(3) That it depends for its action on the formation of a protective film of gas on the surface of the platinum tip, the film being either broken down or increased by wave-induced oscillatory E.M.F.s.

Anodes of great sensitiveness can be made by the method described in the adjacent column.

The Hozier-Brown Electrolytic Detector.—A good account of a most interesting electrolytic detector due to Colonel Sir H. M. Hozier and Mr. S. G. Brown will be found in Dr. Erskine Murray's valuable "Handbook of Wireless Telegraphy." It seems to be a sensitive, reliable and simple instrument.

FESSENDEN APPARATUS.

In back numbers of the American technical journals the reader will find several articles on Professor Fessenden's system, with descriptions of various features, including apparatus called in Professor Fessenden's terminology a wave chute.

The Hot-Wire Detector. — Professor Fessenden has invented an interesting hot-wire detector, the essential part of which is an excessively fine platinum wire.

The method of drawing the wire is very beautiful, though only novel in its present application. A silver wire $\frac{1}{16}$ in. diameter, containing a platinum core ·003 in. diameter is drawn out until the silver is ·002 in., and the platinum, ·00006 in. in diameter. A short loop of this wire is securely fastened to two wires W W, Fig. 854, suitably held in a glass support, G. The tip of the loop is then dipped in nitric acid, which dissolves the silver, leaving an exquisitely fine filament of platinum F, the resistance of which usually lies between 300 and 600 ohms.

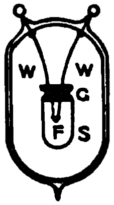


FIG. 854.—PROFESSOR FESSENDEN'S THERMAL DETECTOR.

To facilitate radiation it is enclosed in a silver shell S, which is attached to the glass support G. The shell is then enclosed in a glass bulb, the wires are sealed in and the bulb exhausted. When the oscillatory currents from the aerial pass through the loop it is heated, and its resistance increases, producing a change in the value of current supplied by a battery placed in opposition to a potential-divider; the minute changes in the current operate a telephone.

DR. FLEMING'S THERMAL DETECTOR.

In 1890 Dr. Fleming discovered that if the carbon filament of an ordinary glow lamp be surrounded by a metal cylinder, a current could be passed between the filament and the cylinder if the following conditions were satisfied : The negative pole of the source of current must be connected to the end of the filament which goes to the negative pole of the battery supplying the lamp, while the positive pole of the source of current must be connected to the cylinder. If the source of current is reversed there is no flow. Accordingly the apparatus acts as a rectifier and if inserted in the receiving circuit of an aerial it will cut off half of the wave and will enable the pulsating portion of the wave which is not cut off to actuate an ordinary sensitive galvanometer. Dr. de Forest has used an instrument which is almost identical, and which he has named the " Audion."

SECTION XIII.

TELEPHONY.

CHAPTER I.—TRANSMITTERS, RECEIVERS AND AUXILIARY APPARATUS.

**TRANSMITTERS: BLAKE—GOWER—GRANULAR CARBON—HUNNINGS' CONE—SOLID BACK.
RECEIVERS: BELL—ADER—WATCH. SIGNALLING APPARATUS—PROTECTIVE DEVICES.**

THE electrical reproduction and transmission of sound was first accomplished by Philip Reis when, in 1861, he invented the appliance to which he gave the name of telephone. This instrument was really intended for reproducing music and was of no practical value for transmitting speech, although some spoken words had been transmitted by it. In principle it depended on the discovery in 1837 by Dr. Page, of Salem, Mass., that an electromagnet will emit a sound if the electric circuit be made or broken; this in Reis's instrument was accomplished by causing a stretched membrane to open or close a battery circuit when vibrated by the impact of sound waves. It was not until 1877 that Professor Graham Bell invented the first practical magnetic telephone. This instrument, which is shown in Fig. 855, was composed of a permanent horseshoe magnet A with two soft iron pole pieces P with stalks P_1, on each of which was fixed a small coil of wire B, the ends of the wire being led to two terminals on the wooden base; D is a wooden block on one side of which is mounted, in such a manner as to be free to vibrate, the thin iron diaphragm M. This instrument was used both as a transmitter and receiver, and though now superseded for the former purpose by the modern carbon transmitter, it is the prototype of all receivers at present in use. The action of Bell's telephone differs from that of Reis. If the mouthpiece be spoken into the distribution of the magnetic field is varied by the diaphragm vibrations, and consequently a current of electricity is caused to flow in the conductor in one direction as the lines of the field are moved by the iron approaching, and in the opposite direction as the iron is moved away. These currents flowing over the line to the receiver diminish or increase its magnetism, so causing its diaphragm in turn to vibrate and to reproduce the spoken sounds. No battery was used with this

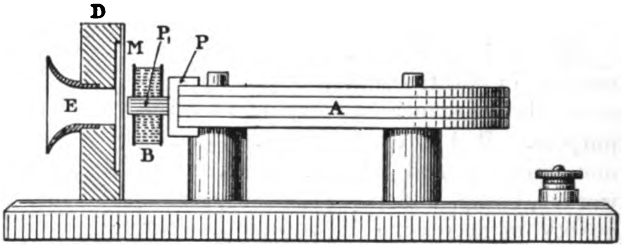


FIG. 855.—BELL'S TELEPHONE.

instrument, the necessary currents being entirely generated by the vibrating diaphragm; and although the articulation was clear, the sounds reproduced were rather faint.

Hughes, in 1878, showed by his microphone that any loose contact between two conductors would act as a telephone transmitter. The microphone consists of a carbon pencil A, as shown in Fig. 856, held loosely between two carbon blocks, in which are formed hollows to receive the pencil; the blocks are connected to a battery and receiver and are mounted on a sounding board. This instrument is very sensitive, and has been reproduced in many forms as a transmitter.

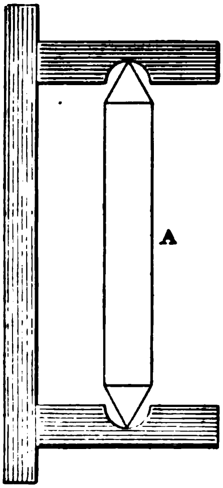


FIG. 856.—HUGHES' MICROPHONE.

TRANSMITTERS.

Carbon is now used for the variable contact in all transmitters, and appears to be the substance best qualified for the purpose. It has excellent properties, is non-corrosive and non-corrodible, easily worked, cheap, and possesses the peculiar quality of decreasing in resistance when heated.

The theory of the action of carbon has been much discussed, and several explanations have from time to time been given. Of these, the most probable perhaps is that the change of resistance in the transmitter is due to variations in the area of contact of the electrodes, this area being decreased by decrease of pressure with a consequent increase of resistance resulting; an increase of pressure produces an opposite effect.

It is proposed here to describe a few typical modern transmitters.

BLAKE'S TRANSMITTER.

This transmitter has been very extensively used both in America and in this country, and is shown in Fig. 857. The sheet-iron diaphragm E, insulated from the frame by a rubber ring stretched round its outside edge, is firmly held in position by two springs, each resting against it and insulated by rubber pads. At the top of the cast-iron ring is a lug H, to which is secured the adjusting lever A whose lower end rests against the screw G; a projection at the other end of A carries the spring B, terminating in the platinum contact piece J and the steel spring C, in the end of which is screwed a brass block carrying a carbon disc; both these springs are carefully insulated from each other. The platinum point is made to touch the

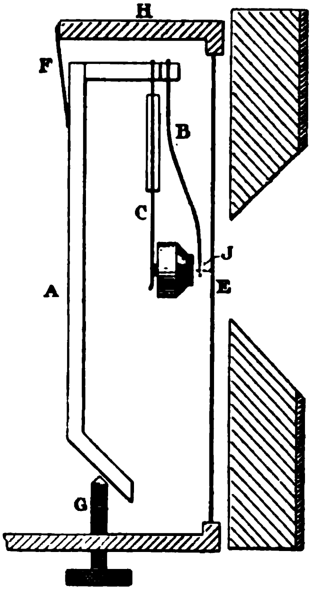


FIG. 857.—BLAKE TRANSMITTER.

diaphragm and the carbon disc, the pressure on the carbon being regulated by the screw G. The circuit is to the transmitter frame, and back through the platinum contact and spring B. The vibrations of the diaphragm vary the pressure of the platinum point against the carbon. This transmitter, though rapidly being replaced by the granular carbon form, works very efficiently on short lines; it is not, however, powerful enough for long distances.

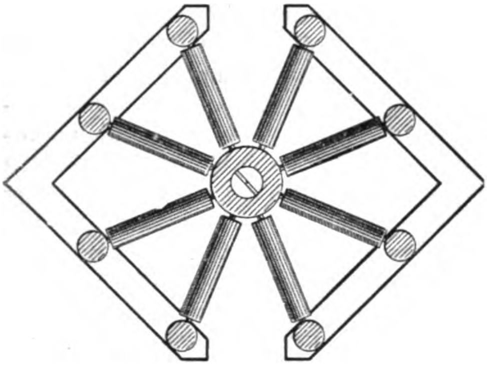


FIG. 858.—GOWER MICROPHONE.

GOWER'S TRANSMITTER.

This was one of the best of the many types of carbon pencil transmitter, and was adopted many years ago by the G.P.O. for private lines. It consists of eight carbon pencils, held in place by one central carbon block and eight outside ones. These eight carbons are divided into two groups of four blocks each, the four in each set being joined together by a copper strip; these are all fixed to the under side of a thin wooden diaphragm held in a sloping position in a teak case, in the top of which is fitted a porcelain mouthpiece to direct the sound to the centre of the diaphragm. The arrangement of the pencils is shown in Fig. 858.

GRANULAR CARBON TRANSMITTERS.

Henry Hunnings, by the invention in 1881 of the granular carbon transmitter, marked the beginning of a new era of telephony. This type of transmitter has now been generally adopted; it excels all others in efficiency and distinctness of articulation. Hunnings obtained his variable resistance by using finely granulated carbon instead of the solid carbon previously used.

Transmitters of this type, however, are liable to trouble through "packing," the continued vibrations causing the carbon to settle down in the bottom of the chamber in an almost solid mass, and many devices have been invented to overcome this serious fault.

HUNNINGS' CONE TRANSMITTER.

In this a carbon diaphragm is used, the back plate, also of carbon, being divided into a number of pyramid shaped cones, on the points of which are fixed small tufts of silk, these damp the diaphragm vibrations and help to prevent "packing" by keeping the carbon granules in place; the construction of this transmitter will be understood from Fig. 859. A special form has been devised in order to allow of its being fitted in existing Blake transmitter cases.

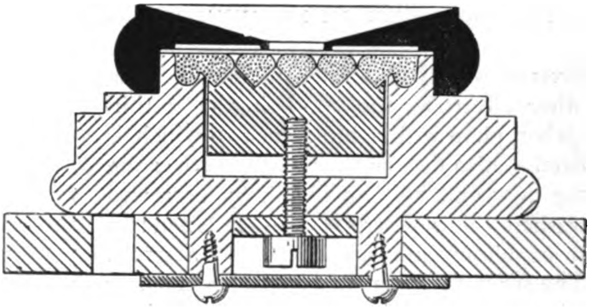


FIG. 859.—HUNNINGS' CONE TRANSMITTER.

THE SOLID BACK TRANSMITTER.

This instrument is the latest development in carbon transmitters and in it the tendency of the granules to pack has been practically overcome.

The construction will be understood by a reference to Fig. 860; the back electrode consists of a thin carbon plate fixed to a brass piece by which it is held in the hollow chamber W, the inner sides of which are covered with paper, in front of this is the other electrode, also consisting of a thin carbon plate with a brass back to which is fixed a mica disc large enough to cover the top of W, and held against it by a screwed washer. This electrode is also fastened to a stout aluminium diaphragm by a screw. The space between the electrodes is partly filled with fine granular carbon. W is held in place by an arm screwed to the frame of the transmitter, round the diaphragm is fitted an indiarubber ring, and against this press two short steel springs, whose ends are covered with rubber, which both hold the diaphragm in position and also damp its vibrations. The mica disc covering W is thin enough to allow the front electrode to move when the diaphragm is caused to vibrate.

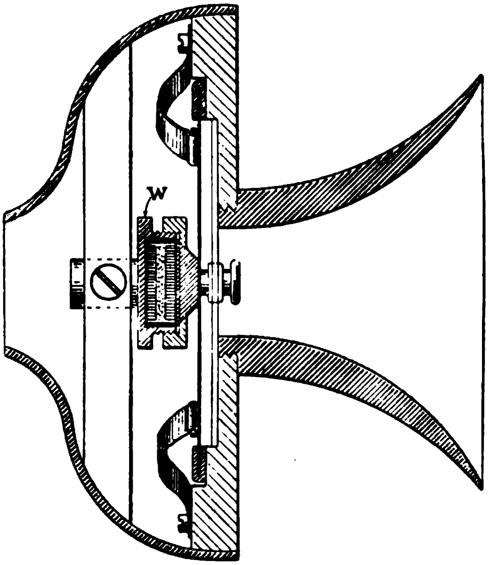


FIG. 860.—SOLID BACK TRANSMITTER.

It was early found in practice that with the transmitter and line joined in series, the variations in resistance produced by the transmitter were in so small a ratio to the total resistance of the circuit, that only small current changes could be produced by them. This difficulty was overcome by inserting in the circuit an induction coil, the secondary winding of which is joined direct to line, the primary being connected in a closed circuit with the battery and transmitter. This arrangement enables the total resistance of the whole primary circuit to be kept very low, so that the variations produced by the transmitter bear a high ratio to the total primary resistance, resulting in greater effect. Many experiments have been carried out with a view to determining the best dimensions for telephone induction coils, and on the next page are given the results of those made by the Swiss Telephone Department, as quoted by Messrs. Preece and Stubbs.[*] A Blake transmitter having a coil with a resistance in the primary of 1·05 and in the secondary of 180 ohms was used as a standard, and with this comparisons were made by tests over five lines, all differing in length. In general the tests showed that a coil which was good for short distances was also good for long.

Telephone induction coils are usually made by being wound over a core of thin annealed iron wire, carefully covered with paper soaked in paraffin wax, the primary consisting of fairly heavy cotton-covered copper wire; this is again covered with waxed paper, over which are wound the many turns of silk-covered secondary wire. The writer has found from experience that the insulation of the coil, and its consequent efficiency, can be greatly increased by standing it on end, after winding, in paraffin wax heated to a temperature of 212° F. The temperature is kept up until all bubbles have ceased to rise from the coil, when the wax is gradually allowed to cool, and the coil withdrawn when the wax is actually on the point of setting; by thus withdrawing the coil the greatest possible amount of wax is absorbed by it.

---

[*] "Manual of Telephony."

Primary Winding.				Secondary Winding.		
Number of coil.	Number of convolutions.	Gauge of wire in millimetres.	Resistance in ohms.	Number of convolutions.	Gauge of wire in millimetres.	Resistance in ohms.
1	61	·5	·25	1,956	·15	100
2	62	·5	·25	3,191	·15	180
3	62	·5	·25	4,080	·15	250
4	116	·5	·50	3,952	·15	250
5	230	·5	1·00	3,865	·15	250
6	232	·5	1·20	4,420	·15	300
7	295	·5	1·50	4,278	·15	300
8	368	·5	2·00	4,735	·15	350
9	368	·75	1·17	4,735	·30	130·2
10	1,350	·5	10·00	3,950	·15	400

Distances in Kilometres.									
0·5		61·6		79·1		85·3		107·4	
Intensity.	Clearness.	Intensity.	Clearness.	Intensity.	Clearness.	Intensity.	Clearness.	Intensity.	Clearness.
·3	·9	·9	1·0	·3	·7	·7	·8	·2	·9
·7	·9	1·0	1·1	·9	1·0	1·0	1·3	·7	1·0
·9	·9	1·0	1·3	·9	1·0	·9	1·3	·6	1·0
1·5	1·3	1·7	1·5	1·3	1·5	1·3	1·5	1·2	1·5
1·3	1·0	1·3	1·2	1·1	1·3	1·3	1·5	1·0	1·3
1·5	·9	1·6	·9	1·7	1·3	1·7	1·6	1·5	1·5
1·3	·9	1·5	·9	1·1	1·1	1·5	1·4	1·6	1·3
1·3	1·0	1·5	·9	1·1	1·0	1·5	1·4	1·6	1·2
1·7	1·0	1·6	·9	1·7	1·4	1·6	1·6	1·7	1·3
·3	·3	·3	·5	·3	·3	·3	·4	·3	·1

TABLES SHOWING RESULTS OF EXPERIMENTS BY THE SWISS TELEPHONE DEPARTMENT AS TO THE BEST DIMENSIONS FOR TELEPHONE INDUCTION COILS.

TELEPHONE RECEIVERS.

The Bell telephone, already described, was the forerunner of all receivers in use to-day. A good receiver should embody the following points: it should be of strong and of simple construction so as to withstand rough usage and render easy the replacement of any damaged parts; it should also be light, of convenient shape, and so constructed that variations of temperature or careless handling will not alter the relative adjustment of the diaphragm to the magnet.

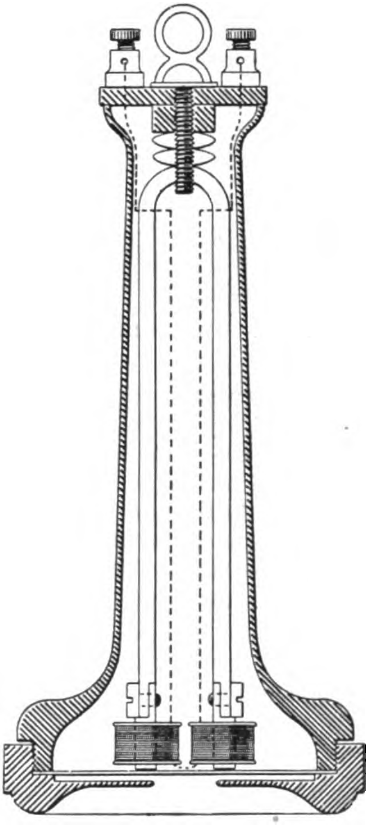


FIG. 861.—DOUBLE-POLE BELL RECEIVER.

THE BELL RECEIVER.

This originally consisted of a laminated single-pole permanent magnet provided with a soft iron pole piece upon which a coil was wound. The double-pole receiver, now universally used, is shown in Fig. 861 and consists of a powerful horseshoe permanent magnet to each pole piece of which is fixed a small bobbin, wound with silk-covered wire ; these bobbins are joined up in series, and the wires led to terminals fixed in the vulcanite case. In some types of double-pole receiver the magnet, instead of being of one piece, is compound and composed of four flat steel bars as in the single-pole type.

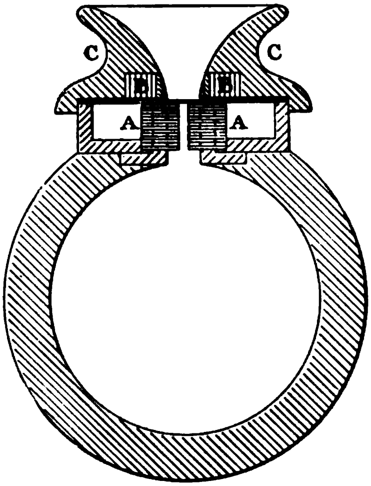


FIG. 862.—ADER'S RECEIVER.

ADER'S RECEIVER.

The permanent magnet in this receiver is circular and has fixed on its soft-iron pole pieces the two coils A, A, Fig. 862. A special feature of this instrument is the "over exciter" (*surexcitateur*), which consists of a soft iron ring B imbedded in the earpiece C, by means of which the magnetic lines are concentrated through the diaphragm and the maximum magnetic result obtained.

WATCH-SHAPED RECEIVERS.

These, though not very powerful, are often used on short lines. In some forms the magnet is circular, having two horns which project at right angles to the plane of the magnet, and form the poles to which are fixed the coils. The ring magnet is magnetised so as to produce consequent poles. In the case shown the magnet M is semi-circular, with horns projecting towards the centre.

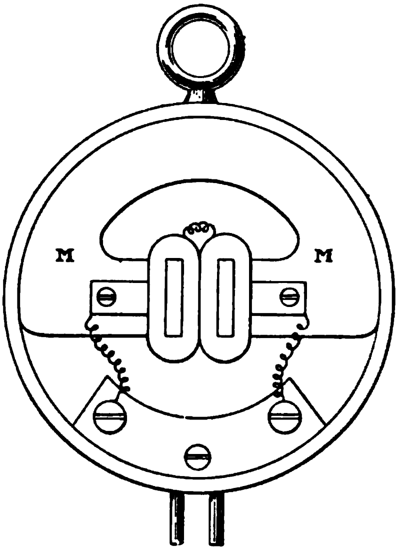


FIG. 863.—WATCH RECEIVER.

SIGNALLING APPARATUS.

In order that one user of a telephone may call another, a means of exchanging signals must be supplied. For this some form of electric bell is universally used, operated either by a magneto-generator or by a battery.

THE TREMBLING BELL.

The operation of a trembling bell has been described on page 218. For telephone work it is largely used for short distances, but has been displaced for exchange work by the polarised bell, operated by a magneto generator.

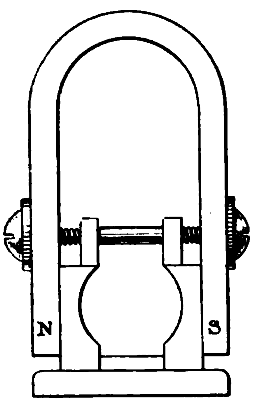


FIG. 864.—MAGNETO FIELD-MAGNET.

THE MAGNETO-GENERATOR.

The alternating current required to ring the polarised pattern of bell is generated by a small magneto-electric machine. It consists of three permanent steel horse-shoe magnets, arranged side by side, and clamped on to a common pair of pole pieces made up of two iron castings, held together by brass bolts. The pole pieces are bored out so as to just allow a small **H** armature to revolve freely within them; the magnets and pole pieces are shown in Fig. 864.

The armature is a soft iron casting of the shape shown in Fig. 865; it is wound with silk-covered wire, and at each end of the web is a cylindrical extension which is turned to fit the two bearings carried on the ends of the pole pieces. One end of the armature winding is connected to a pin *a* screwed into the armature, and the other end is joined to a pin *b* insulated from the armature, but connected to *c*. On one end of the armature spindle is fixed a small toothed wheel, which engages with a larger wheel fitted with a driving handle. The armature is wound with six or eight mil. (·006 in. or ·008 in. diam.) wire to about 400 ohms, in about 3,000 to 4,000 turns. The voltage at a moderate speed (300 revolutions per minute) is rather over 50 volts. The gearing usually increases the speed of the armature as compared with that of the handle in the ratio 1 : 5.

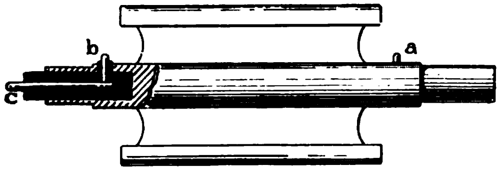


FIG. 865.—MAGNETO ARMATURE CORE.

The Automatic Cut-out.—The highly inductive resistance of the armature winding would have a serious effect on the speaking if left in circuit during conversation, a device called a cut-out is therefore used, by means of which the armature coil is short circuited when not actually in use. A common and very satisfactory one is shown in Fig. 866.

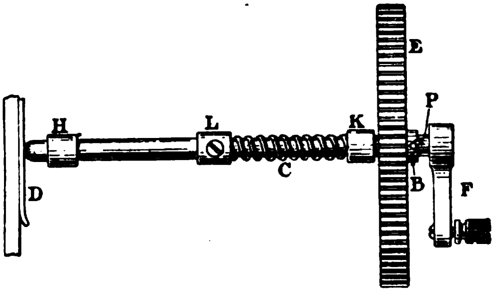


FIG. 866.—AUTOMATIC CUT-OUT FOR MAGNETO.

E is the large toothed driving wheel which gears with the smaller wheel made fast to the armature, and rides loosely on the spindle. On one side is cast the shoulder B, in which a **V**-shaped recess is cut. H and K are the spindle bearings, and are attached to the frame of the generator, and L is an adjustable collar secured to the spindle by a grub screw.

One of the terminals of the armature is connected to the frame, and the other to the contact D, so that when the generator is at rest the armature is short circuited through D and the spindle, the latter being kept in contact with D by means of the pressure exerted by C between L and the fixed bearing K.

When the handle F is turned, the small pin P slides up the side of the recess in B before E commences to revolve, and so the whole spindle moves outwards and breaks contact with D and the short circuit ceases.

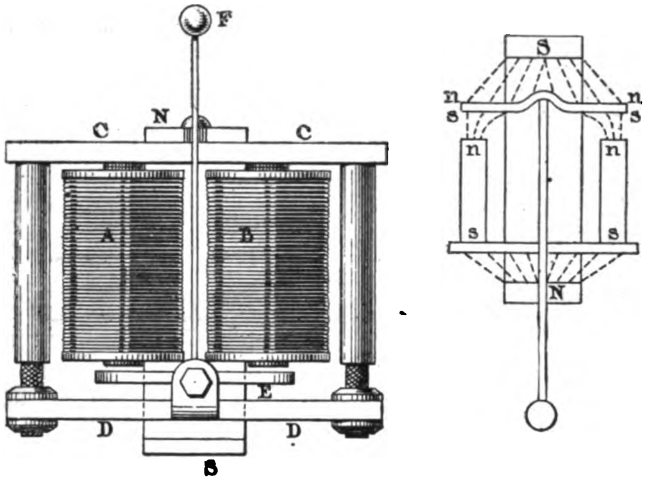


FIG. 867.—POLARISED BELL.

THE POLARISED BELL.

This is shown in Fig. 867. It consists of two coils A, B generally wound to a resistance of 500 ohms each, mounted on cores carried by a soft iron base C C, to the centre of which is screwed the pole N of a permanent magnet shaped thus . D D is a bar of thin brass between two projections to which is pivoted the armature E carrying the bell hammer, F. Two gongs are provided, one on each side of the hammer, so that it may strike them alternately if it is kept vibrating. The pole S of the permanent magnet already referred to is bent so as to come over the outside of D, just below the centre of E, which it polarises by induction, making the middle of north and the ends of south polarity; the ends of the cores of A and B are of north polarity, owing to the induction of N. If now a current be passed through the coils the N pole of one core will be strengthened, and that of the other weakened, and the armature is in consequence attracted to the stronger pole; on the current being reversed the opposite effect will be produced, the coil previously strengthened being now weakened and *vice versa*, so that the armature is caused to vibrate from one pole to the other so long as an alternating current flows, and thus causes the hammer to strike against the bell gongs.

THE SWITCH HOOK.

The switch hook is a piece of apparatus by means of which the signalling portions of a circuit are automatically cut out during conversation and again switched in when required. Its usual form is that of a long lever, one end of which is formed into a hook to hold the receiver, the other end being pivoted. On hanging the receiver up, its weight pulls down the lever and causes it to make circuit against a contact connected to the bell and generator; if now the receiver be removed the pressure of the spring will cause the lever to rise to its upper position when the circuit, with the bell, etc., will be broken and a circuit made through the secondary winding of the induction coil, and also the closed primary transmitter circuit completed. A reference to Fig. 868 will make this clear. If this station were rung up the current would pass through the line L_1, cut out of generator M to bell B_1, which would be of the polarised type, and back through lower contact of switchhook H and switchhook to return line L; on the receiver being removed from the hook the bell contact would be broken, and the circuit would then be through line L, switchhook H, right hand upper contact, secondary of induction coil S, receiver R, and back to line L_1; the transmitter circuit would also be completed from battery B, through primary winding of induction coil P, right hand upper contact, switchhook H, left hand upper contact, transmitter T, and back again to battery; in each diagram the completed circuits are shown by the full lines. In a system as shown above the subscriber would ring his own bell when ringing up; in the latest instruments this has been overcome by a device similar to the generator cut-out already described.

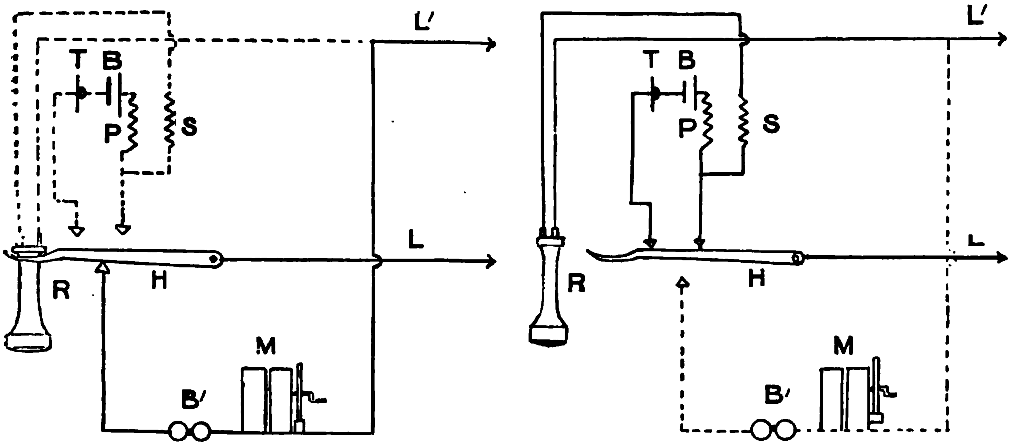


FIG. 868.—SWITCH HOOK CIRCUITS.

PROTECTIVE DEVICES.

It is necessary that the apparatus and the circuit generally shall be protected from the effects of lightning and other currents of high voltage. To this end every telephone should be supplied with some form of protector, as should also each subscriber's line where it enters the exchange. The simplest and probably the most used form, on instruments at any rate, consists of three brass plates fixed as close together as possible without quite touching each other; one of the plates has an edge of sharp saw teeth and is connected to earth; the lines come on to the other two plates. Any high voltage current striking the lines will spark across the gap to the earth plate and thus be conducted into the ground. This form of arrester is open to some objections, among others, that the plates, to be of any use, have to be adjusted very close to each other, and any warping of the wooden bell case on which they are fixed may cause them to make contact and thus short circuit or earth the line; on the other hand, if the plates are not closely adjusted they may fail in their object.

A form of arrester adopted by the General Post Office consists of two circular brass plates between which is placed a thin mica disc pierced with three small holes round a larger central one; the line is connected to the upper plate and earth to the lower, the action being the same as in the arrester previously described, *i.e.* the current sparks across the narrow gap between the two plates left by the holes in the mica.

Another method of protection is to place in circuit a small fuse of very low carrying capacity; this, in some cases, is mounted on small mica strips and so designed as to be easily inserted under the line terminal screws of the instrument.

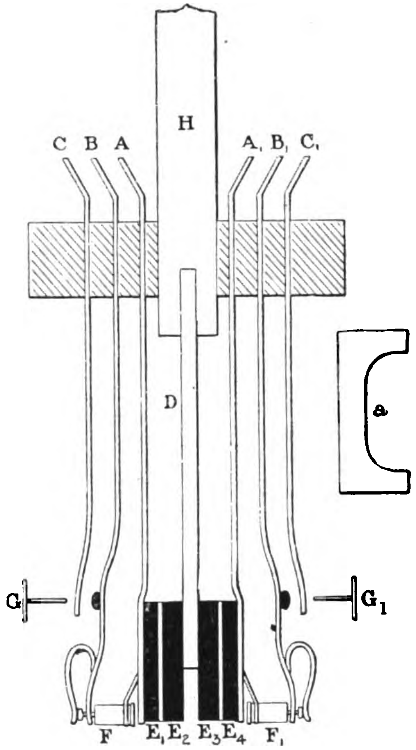


FIG. 869.—HEAT COILS AND SUPPORT.

It may happen, however, that the current, although not sufficient to blow a fuse or flash across a lightning arrester will, if permitted to flow for any length of time, develop sufficient heat in a subscriber's line indicator or even in the switchboard wiring, to cause the insulation to burn up, and may even set the exchange on fire. For protection against such a current a device, called a thermal arrester or heat coil, is used, fitted in conjunction with some type of lightning arrester; this is usually placed where the outside wiring joins the wires to the switchboard in the exchange test room, but it is becoming common practice now to fit some device of this sort at the subscriber's end of the line. Such a protector, adapted for test-room use, is shown in Fig. 869, and consists of an iron base H carrying, insulated from it, six flat springs of German silver or other suitable metal. The pair of springs A, A_1 nearest the base plate take the outside cable wires and make contact against two small carbon blocks E_1, E_4; against these blocks, but insulated from them by a thin mica washer of the shape shown at *a* (Fig. 869) are fitted two other carbons E_2, E_3 which are in contact with the base plate through the bar D, and have in their centres a small hole filled with an alloy of bismuth and lead.

The second pair of springs B, B_1 carry the wires to the testjack and exchange, and are connected to the first pair by small coils of German silver wire F, F_1 wound on tubes. The springs A, A_1 are set so that they press the carbon blocks together (though always separated by the mica slips) and into contact with the bar D. The springs B, B_1 are set outwards but are not so strong as A, A_1, and the coils F, F_1 are held by tension between the ends as shown. The outer attachment is by a fusible pin, whose head is slipped under the tip of a light horseshoe shaped spring clip carried by the lower end of each jack spring B. One end of the German silver coil is connected to this pin and the other end to the insulated flange at the other end of the coil, which flange also forms the inner attachment to the line spring A by a spring clip. The path of the current through the apparatus is as follows: from the outside wiring through spring A and heat coil to spring B, thence through the exchange connections and back to spring B_1, through heat coil and spring A$_1$ to outside wire again. The springs C C$_1$, are connected to a battery and bell to whose other side are connected the contacts G, G$_1$; if the coils get hot and melt the fusible pins at their outer ends, the springs B, B$_1$ will fly out and force springs C, C$_1$, against, G, G$_1$, so causing the bell to ring, and giving notice of the trouble. Should a high-tension current strike the line not only will the coils fuse, but the current will arc across the spaces between the two carbon blocks, melting the fusible alloy and short circuiting them, thus putting the line dead to earth. The heat coils, however, will operate to melt the fusible pins if a small current (but above the normal) flows for a long time.

CHAPTER II.—TELEPHONE SYSTEMS AND SWITCHGEAR.

SIMPLE TELEPHONE CIRCUITS — SMALL SWITCHBOARDS — SWITCHBOARDS FOR PUBLIC EXCHANGES—BRANCHING JACK AND SELF-RESTORING INDICATOR SYSTEM—WIRING OF MULTIPLE SWITCHBOARDS—TESTBOARDS—TESTING—CENTRAL BATTERY SYSTEMS —MISCELLANEOUS EXCHANGE SYSTEMS.

THE simplest form of telephone circuit is one with two instruments connected by a single wire and having their other terminals connected to earth ; instead of using earth, a second or "return" wire can be run, in which case the circuit is said to be a "metallic" one as distinguished from an earth or single circuit ; single circuits are now used for only very short lines, the use of the metallic circuit for exchange and long-distance work being universal. Next in simplicity to the circuit described above is one in which there are three instruments joined together either in series, as in Fig. 870, or in bridge or parallel, as in Fig. 871. The dotted lines show the metallic circuit connections in both cases. The bridge method of connecting is the more satisfactory as in it the resistance of the centre or intermediate instrument has not to be spoken through when the two terminal stations are engaged in conversation, nor will a fault on the intermediate line necessarily stop the other stations from communicating with each other. Also several instruments may be joined up on the bridge system without injuriously affecting the speaking properties of the line. In either system any station can overhear the conversation of any other; also when one station rings up, all the other stations receive the ring, and this necessitates the arranging of a code of signals so that only the desired station may answer.

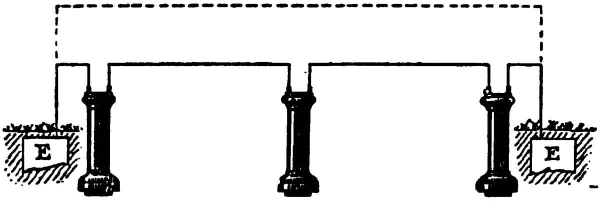


FIG. 870.—ELEMENTARY TELEPHONE CIRCUIT.

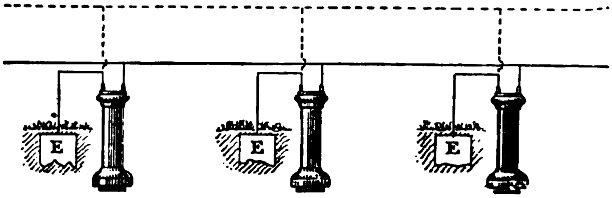


FIG. 871.—TELEPHONE CIRCUIT "BRIDGE" CONNECTED.

Where only three instruments are in the circuit it is usual to use an "intermediate switch" which may be either of the "stop" pattern (in which case the intermediate station can communicate with either of the terminal stations but cannot put them through to each other) or of the "through" type, which allows any two of the stations to intercommunicate. In both forms of switch the connections are generally so arranged that an "extension bell" is joined up to that line with which communication is not being held, so that signals may be received from it. Where more than three instruments are to be joined up, a piece of apparatus known as a switchboard is used, on which arrangements are made whereby each subscriber can signal to an operator stationed at the board who, on ascertaining his requirements connects him to the line he desires by means of flexible connecting cords and plugs. Each line coming on to the switchboard passes through a spring or "switchjack" consisting usually of four springs arranged on a vulcanite base and insulated from each other; they are so adjusted that each outside spring makes contact by means of its own pressure against the inside spring next to it forming the line connection. The outside lines come on to the two outside springs, the inside pair being joined to an indicator consisting of an electromagnet, with an armature carrying an arm, so arranged that a current traversing the coil will attract the armature and release a small hinged shutter. The dropping of this shutter indicates that the subscriber whose indicator it is, wishes to call the exchange. Fig. 872 gives a side view of a small form of spring jack and Fig. 873 a form of indicator manufactured by the Western Electric Company. It has two coils, only one of which can be seen in the illustration, and the cores of these are connected by an iron strip forming a yoke. A is the armature to which is attached the arm D; P is the shutter which is normally held up by the catch at the end of D. If now a current be passed through the coil, A will be attracted to the pole piece of M, and D being tilted up, P is released and falls forward; in so doing it causes the spring S to press against the point of screw C, this completes the circuit of a trembling bell and battery which continues to ring until the shutter P is restored to its original position. Fig. 874 shows another form of indicator known as the "tubular" or "ironclad"; there is only one coil M, which is covered with a tubular iron case, F; the armature A is pivoted at C and fitted with an adjusting screw and lock nut which regulates the armature play. P is the shutter pivoted between the plate G and the face of the indicator; an alarm bell contact, not shown, is fitted as in Fig. 873. The coil is wound to a resistance of 1,000 ohms; the impedance of this coil is very high, and in consequence it does not injuriously affect the speaking of a line when bridged across it. This is the type of indicator used on the board shown in Fig. 877.

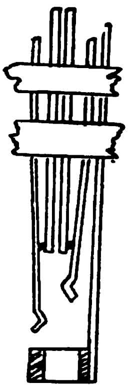


FIG. 872.—EXCHANGE SWITCH-JACK.

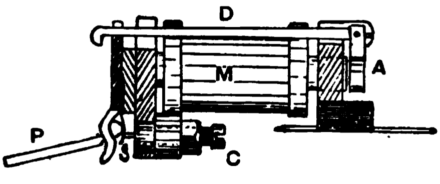


FIG. 873.—INDICATOR.

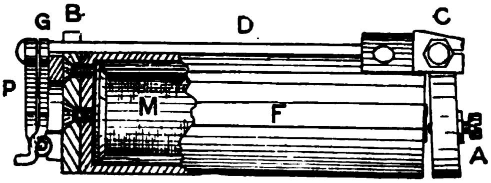


FIG. 874.—IRONCLAD INDICATOR.

On each outside spring of the jack, in addition to the line wire already mentioned, is another wire going to a terminal; these terminals are arranged in pairs, one pair for each line, and to them is attached a two-conductor flexible cord ending in a plug (Fig. 875), this plug fits the spring jack (Fig. 872), and on being passed into such a jack forces the two outside springs away from the inner two, thus disconnecting the indicator and allowing the outside springs to rest on the plug, the short spring on the tip of the plug, the long spring on the brass sleeve. Fig. 876 shows the complete circuit of one subscriber's line on a switchboard such as is being described, and Fig. 877 gives views of the board. The position of the apparatus in each case is as follows: A, indicators; B, jacks; C, plugs; D, plug terminals; E, line terminals; and F, weights keeping plug cords taut.

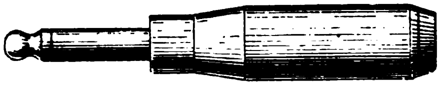


FIG. 875.—PLUG.

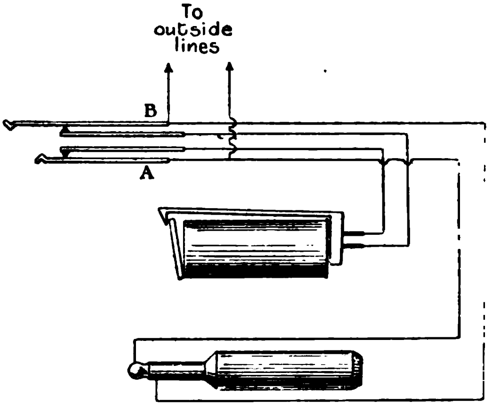


FIG. 876.—PLUG CIRCUIT.

When a subscriber rings up, the current from his generator passes to line and spring A of jack, Fig. 876, thence through the inner spring to the indicator and back by the other two springs to line B and generator again; this drops the indicator, on seeing which the operator takes a plug attached to her instrument and by inserting it into the jack associated with the indicator puts herself in circuit with the subscriber; having ascertained the number he requires she withdraws her plug and inserts it into the jack of the wanted number, which she rings; having obtained a reply she once more withdraws her plug and taking that of the calling subscriber inserts it into the jack of the number called; the two subscribers are now connected through to each other, the indicator of the called subscriber being cut out and that of the calling subscriber being bridged across the line; this indicator, owing to its high resistance and inductance, does not seriously affect the rapidly fluctuating

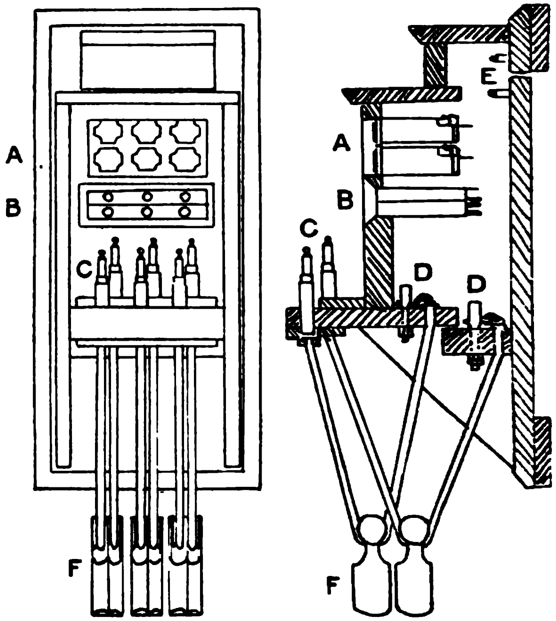


FIG. 877.—SMALL EXCHANGE BOARD.

speaking current. On finishing the conversation both subscribers hang up their receivers and ring, thus dropping the indicator of the calling subscriber, which shows the operator that she may clear the connection. Boards of this type are largely used by firms who are connected to a central public exchange and also have lines to each of their various departments or offices. The indicators in such a board are always of the tubular type, as these are of the requisite high resistance and impedance.

SWITCHBOARDS FOR PUBLIC EXCHANGES.

Switchboards of the types just described are seldom made for more than 30 lines, and where the number to be dealt with exceeds this, or for public exchange work, further arrangements are usually made on the board to facilitate the manipulation of the various calls.

A pattern of switchboard much used is the "Standard," made by the Western Electric Company (Fig. 878); this board has a capacity of either 50 or 100 lines, and the arrangement of the various parts is as follows:—The upper section of the board contains rows of subscriber's jacks, and below these are the subscriber's indicators. Another row of jacks is also provided, to which are connected junction lines to other boards should the number of subscribers render the use of these necessary, so that subscribers on any boards can be connected together. In the top of the board at the back, is fitted a panel through which are fixed brass tabs; to the outside end of these tabs is connected the cable carrying the wires from the subscribers, while the inside ends are permanently wired to the line or outside springs of the jacks, these are generally of the five-point pattern (Fig. 872), and are used in connection with three-way cords and plugs. The "answering" and "calling" plugs are placed in pairs on a shelf immediately below the jacks. The answering plug would be just behind the calling plug shown in the sectional view. The line indicators are as in Fig. 873, the ring-off indicators of the tubular type, and of 1,000 ohm resistance; as the line indicators are cut out during conversation they are wound to a resistance of 100 ohms. The operator's instrument is of the standard exchange type, having the transmitter fixed on a breastplate and a light receiver held on by means of a steel band; the whole is connected by a five-way flexible cord to a plug, and a jack to fit this plug is fitted on the switchboard, in which the operator keeps her plug inserted while on duty. On a panel below the jacks are fitted ten ring-off indicators, and on a shelf immediately in front of these is fitted a row of listening keys by means of which the operator can put herself in circuit with any pair she desires; two ringing keys are provided in front of the listening keys, and in the centre of the shelf. The induction

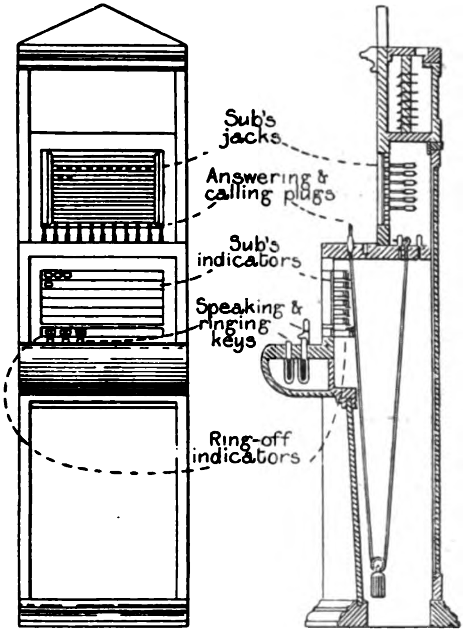


FIG. 878.—"STANDARD" SWITCHBOARD.

coil for the operator's instrument is fitted inside the keyboard; it is differentially wound, and the connections will be seen in Fig. 879. It will also be well to mention here that the operator's receiver has in addition to the usual two terminals, a third one joined to the centre of the coil and to earth, this is required in connection with the "engaged test" on multiple switchboards, and will be explained in detail later on.

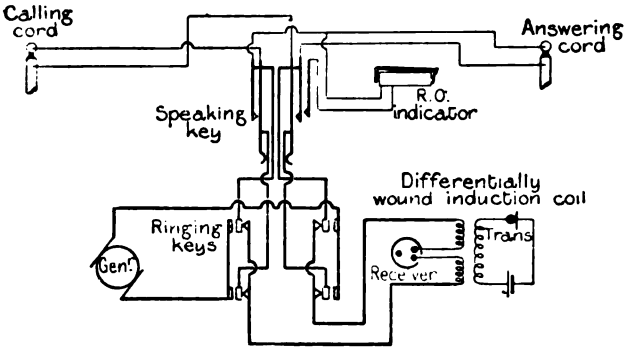


FIG. 879.—CONNECTIONS OF "STANDARD" BOARD.

An end view of both speaking and ringing keys is given in Fig. 880. They consist of flat springs mounted on vulcanite bases. A reference to the drawing of the speaking key will show that it consists of five springs; when the key is in its normal or through position, the connections are such that the two cords are joined through to each other, having the ring-off indicator bridged across them, the operator being out of the circuit. When the operator depresses the key she causes the springs to break away from each other and make instead on four contacts which are connected through the ringing key to the receiver, these four contacts are common to all the speaking keys, so that on any one being depressed the pair of cords belonging to it are immediately connected to the operator. The action of the keys is very simple and will easily be understood on reference to the speaking key in Fig. 880. A is a pivoted cam lever which when in the position shown forces the flat springs apart by means of the round vulcanite piece B, to which it is connected by the plunger C. Over this is fitted a spiral spring having its one end pressing against the collar D and its other against the vulcanite base E; this spring serves to push B away from the flat spring when the cam lever A is returned to the other position. The action of the ringing key is precisely similar except that the operator presses it down with the finger instead of by a lever.

The method of operating is as follows: Supposing subscriber No. 3 rings up, No. 3 indicator drops, and the operator takes the back or "answering" plug of one of the pairs and inserts it into jack No. 3, at the same time depressing the

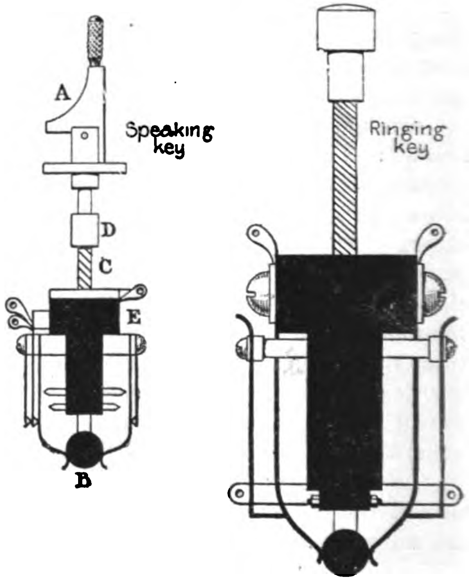


FIG. 880.—SECTIONS OF KEYS.

speaking key of this pair of cords and also, with the other hand, restoring the indicator shutter to its normal position. She is now in circuit with the subscriber, and having asked the number (say 7) he requires, takes the front or "calling" plug of the pair she is using and inserts it into that number (7), ringing by means of the left-hand ringing key (the right-hand key is used for ringing on the answering cord). Having obtained a reply she pushes up her speaking key, cutting herself out of circuit and leaving the subscribers through to each other ; the connections will be easily traced by a reference to Fig. 879. It should be noted that the ringing keys are common to all the cords ; on later pattern boards a key to ring on the calling cords is combined with each speaking key, and one ringing-back key common to all the answering cords fitted. The subscribers having finished their conversation, a turn of their magnetos drops the ring-off indicator, on seeing which the operator clears the connection. In Fig. 879 the common wires are drawn in thick lines, and two-way cords only are shown for simplicity, the third conductor not being used except for multiple switchboards.

One hundred lines per operator, if the subscribers are at all busy, has been found in practice to be too many, and for small exchanges the fifty line boards are generally used. Where there are several boards in use, a subscriber may want to speak to a number connected to a different section from his own, and in order that such calls may be put through, auxiliary lines are run from the bottom row of jacks to all the other sections ; a simple double-ended cord, without speaking key or ring-off indicator may be used on these jacks. With this system of through switching there is considerable delay, and the operators must be given some easy means of communicating with one another. These and other considerations led to the invention of the multiple switchboard, in which, instead of a subscriber being connected to a jack in one position only, he is permanently connected to a jack in every section in the exchange, and any operator can connect any two subscribers at any section. In this system the sections consist of three operators' positions, and have their upper parts divided into six panels in which is fitted a jack for each line in the exchange. These jacks are arranged in groups containing one hundred each, made up of five horizontal rows of twenty jacks each ; the numbering of these begins at the bottom left-hand panel, the

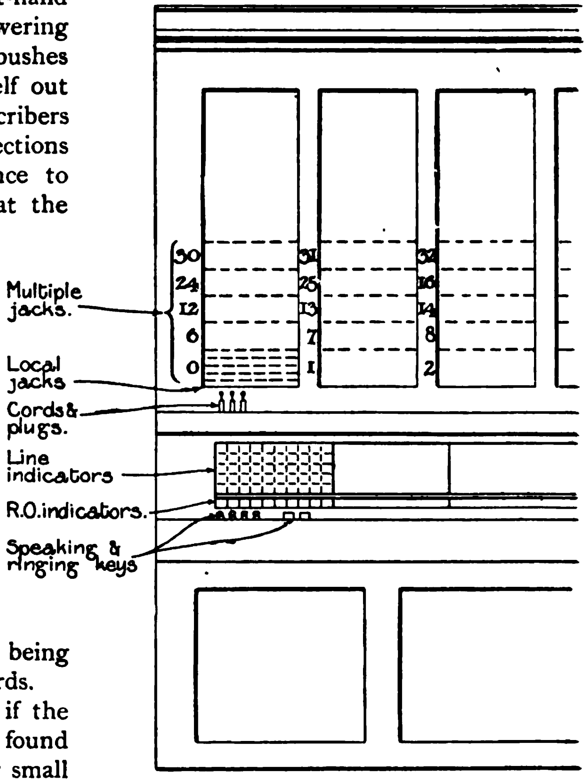


FIG. 881.—ARRANGEMENT OF MULTIPLE SWITCHBOARD.

bottom group in the left-hand panel is numbered 0, the next to the right 1, and so on to indicate the hundreds; 601 will thus be the bottom left-hand jack of the second group up, in the first panel.

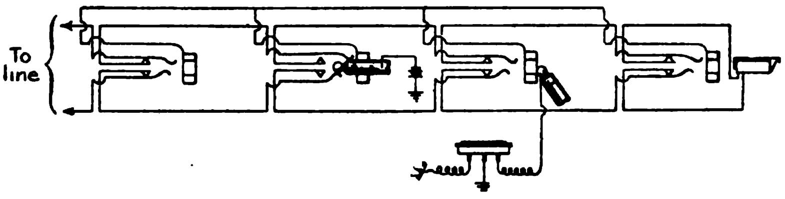


FIG. 882.—CONNECTIONS SHOWING ENGAGED TEST.

Fig. 881 shows the arrangement of the board ; below the multiple are strips of local or home section jacks, belonging to those subscribers allotted to this particular section, two hundred to each section ; these are the jacks on which the operators answer the subscribers, and below them projects a shelf carrying the cords. Below this again are panels carrying the indicators, of the two hundred subscribers whose local jacks are on the section, separated by a wooden strip from the ring-off drops ; a second and lower shelf carries the speaking and ringing keys for the fifteen cords allotted to each operator. The jacks are of the type shown in Fig. 872, and the line and ring-off indicators, speaking and ringing keys as shown in Figs. 874 and 880. The general arrangement is as in the Standard switchboard, the third conductor of the plug-cord is used, however, and connected through a battery to earth, also the bushes or fifth point of the jacks which were left spare in the Standard board are now connected to each other. A switchboard may be formed of any number of sections placed side by side, each having its own two hundred subscribers, in addition to the multiple of all the others, and the sections taken together form the multiple board. It will be evident that on such a board, a line may be engaged on any section and some ready means of ascertaining whether it is or not must be supplied. Fig. 882 shows the method used with jacks of the type shown in Fig. 872, four jacks are shown representing the subscriber's line on three different multiples, the fourth jack (on the right hand) being the home section. It will be observed that the line is engaged on the second multiple, and the earthed battery on the third conductor or sleeve of the plug is connected to the bush of the jack, and also to the bushes of every other jack of that line ; if now the operator, at say the third multiple, be asked for the same number, she will take the calling cord of the pair which she is using, and before inserting it into the jack will tap the tip of the plug on the jack bush, the current will then flow through the plug tip, half the secondary coil and half the receiver coil, giving a click in the receiver telling the operator that the line is engaged.

THE BRANCHING JACK AND SELF-RESTORING INDICATOR SYSTEM.

In the system just described a subscriber's line jacks are connected together in series ; this has been found to have some disadvantages, among others that dirt and grit are liable to get into the jacks and between the springs, causing disconnections. In the branching system now used, all the subscribers' jacks are connected in parallel, and a special line indicator is used, which, instead of being cut out during conversation is permanently bridged across the line. This indicator is a very ingenious device, it consists of two coils mounted on opposite sides of a flat metal plate, each plate usually carrying

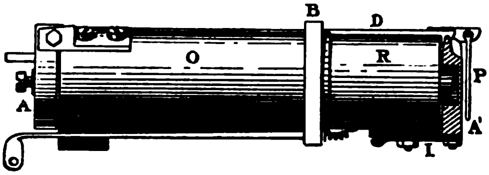


FIG. 883.—SELF-RESTORING INDICATOR.

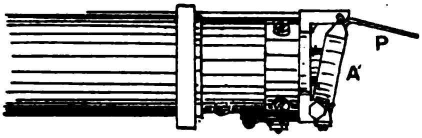


FIG. 884.—INDICATOR OPEN.

ten indicators; one coil is usually known as the operating coil and the other as the restoring coil. The action of the operator in plugging into the subscribers' jack restores the indicator to its normal position. Fig. 883 shows the indicator; O is the operating coil surrounded as in the tubular type in a soft iron jacket, and R the restoring coil similarly enclosed; the armature A has attached to it the arm D, terminating in a catch which holds up the soft iron armature A^1 into a recess in which the end of the core of R protrudes When a subscriber turns his generator handle, current flowing through O attracts A, releasing A^1 which, in falling, presses forward the light aluminium shutter P to the position shown in Fig. 884 and discloses the number painted on A^1. On a current being passed through the coil, R, A^1 is attracted, and being pulled up allows P to fall back; as long as current flows through R, A^1 is held up and will not drop even if D is raised. Fig. 885 shows the jack used; these are made up in strips of twenty, mounted on an ebonite frame. A branch of one line comes on to the branch socket L_1 and of the other on to the spring L_2. T and *t* are used for the test circuit, T being connected to the bush T_1 and the other jacks; the diameter of T_1 is greater than that of the plug, so that they will not be in contact when the latter is in the jack.

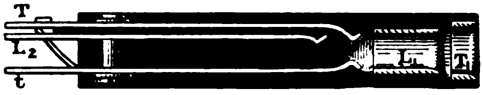


FIG. 885.—BRANCHING JACK.

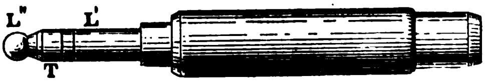


FIG. 886.—TWO-WAY PLUG.

The two-way plug is shown in Fig. 886, it carries in addition to the two-line connections a brass collar T, insulated from the other parts of the plug and serving when the plug is inserted in the jack to connect the springs T and *t* together, the tip L'' makes contact with the spring L_2 and L' with the brass ring L'; the collar on the plug immediately behind L' is covered with vulcanised fibre to prevent contact with T_1. Fig. 887 shows the subscribers' line connections through two multiples

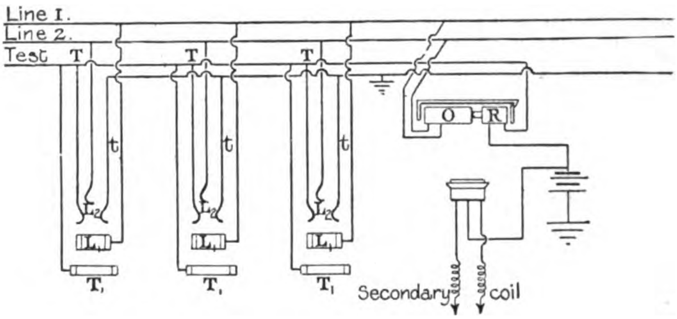


FIG. 887.—SUBSCRIBERS' CONNECTION TO TWO MULTIPLE JACKS AND A LOCAL JACK.

and the local jack ; it will be seen that the springs T are connected to an earthed battery through the restoring coil of the line indicator. When an operator plugs into a jack she connects T and *t* as already described, restoring the indicator and also putting an earth on the bush T_1 ; for the purpose of the engaged test the centre point of the operator's receiver is connected to earth through a battery. The means by which she gets the engaged click are shown diagrammatically in Fig. 888.

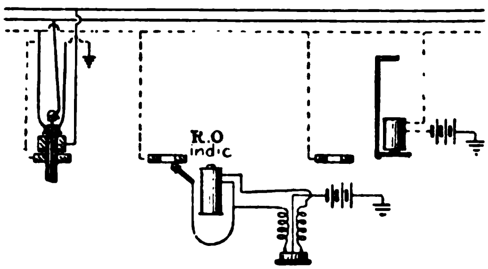


FIG. 888.—ENGAGED TEST.

Fig. 889 is a diagram of the cord circuit, the ring-off indicator is also self-restoring and connected through an earthed battery to a spring actuated by the speaking key. When the key is in its normal position the spring is disconnected, but on depressing it the spring makes contact on a stud connected to earth, and completes the restoring circuit of the ring-off drop.

These arrangements have enabled the operator to attend to a larger number of subscribers than was formerly possible ; in addition to this the indicators can be placed out of reach at the top of the board, thus giving more space for jacks. A study of the circuit will show that during conversation there must always be three indicators bridged across the circuit ; these are wound so as to be of high resistance and have considerable self-induction, and therefore do not harmfully affect the speaking properties of the circuit.

THE WIRING OF MULTIPLE SWITCHBOARDS.

The difficulty of designing a modern board in which all the jacks shall be easily accessible will be understood when it is realised that in a modern central battery board the length of a strip of twenty jacks is only 8·25 in. and the depth ⅝ in., and that each jack has six wires soldered to it, making a total of 120 wires to each strip. The wires are carried to the switchboard in flat cotton-covered cables, each containing sixty-three wires, sixty for the A, B and test lines of the jacks and three

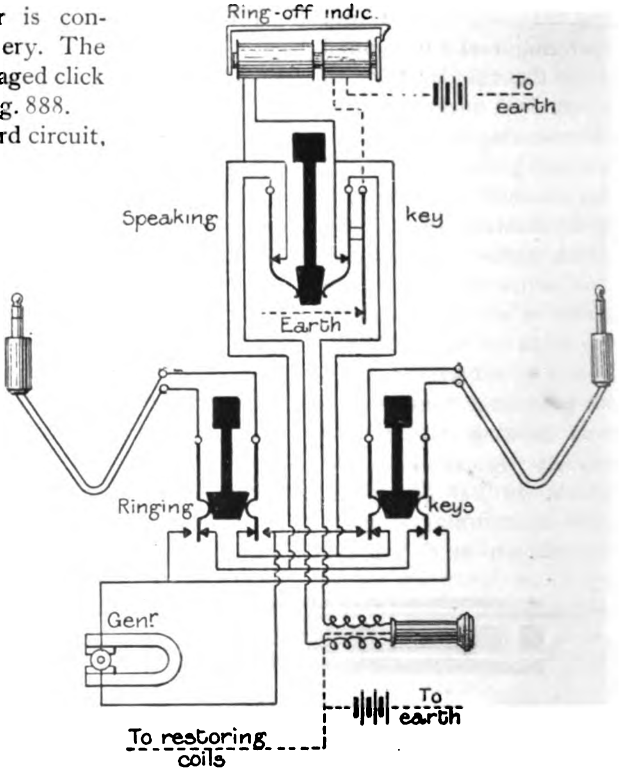


FIG. 889.—CORD CIRCUIT.

spare lines for use in case of wires going out of order in some part of the cable where they cannot be reached. Each wire is covered with a layer of rubber and two layers of cotton or worsted; the outside coverings being of different colours or combinations of colours to enable any particular wire to be identified. The actual connecting to the jacks is usually done in some place where long tables or benches can be fitted to take the forming blocks.

Lengths of cable to the required number are now laid out on the benches, so that behind each strip of jacks are two ends of cable, one coming from the previous strip of jacks and one going to the next strip. The outer covering of both cables is cut away so as to leave the wire uncovered for a length slightly greater than the length of the jack strip plus a length sufficient to allow the wires to reach the jack. About an inch of the end of the wires is bared of insulation, taken through the jack springs and soldered. Great care must be exercised not to remove more insulation than is absolutely necessary, and also to see that the insulation does not run back during soldering. When all the jack strips of one length have been wired they are taken to the switchboard and placed in position. Fig. 890 shows the arrangement of the cables in the board. It will be seen that the length of wire from cable to jack is different on each panel; this allows of a more compact arrangement of cable than would be otherwise possible. The latest pattern of switchboard cable has its covering so treated as to be flame proof, thus greatly minimising the danger from fire.

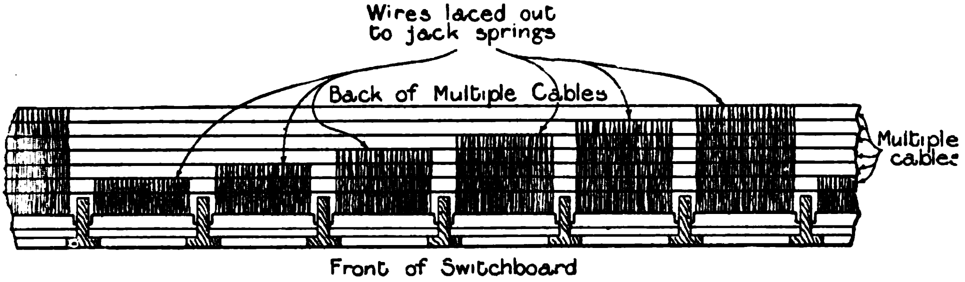


FIG. 890.—WIRING OF MULTIPLE JACKS.

TESTBOARDS AND TESTING.

A necessary part of the equipment of every exchange is a test room, through which all the subscribers' lines pass before going to the switchboard, and where some convenient means of disconnecting any line is provided.

The outside wires are brought in in cables which are terminated on cable bars; these in their simplest form consist of strips of vulcanite carrying terminals for the various wires, and a serrated lightning arrester. This form of cable bar is being replaced by a type consisting of combined heat coils and lightning arresters as already described and illustrated in Fig. 869, each bar has fifty-one pairs of heat coils, and can take a 104 wire cable, two of the cable wires being left spare for use in case of emergency. The connections from the cable bars to the jacks are made by means of wires run between the two and known as cross connections.

Fig. 891 shows one of the latest forms of testjack, though testjacks are not being fitted in the newest exchanges. It consists of a sheet-iron base carrying twenty jacks.

The cross-connection wires from the cable bars are connected to the lower pair of springs, while the upper pair carry the cable wires from the distribution board; the springs are held in a strip of vulcanite. In front of the jacks is a wooden strip pierced by twenty rectangular holes, behind each of which is a small metal dust shutter kept closed by a spring; the insertion of a test plug forces back the shutter, which closes again on the plug being withdrawn.

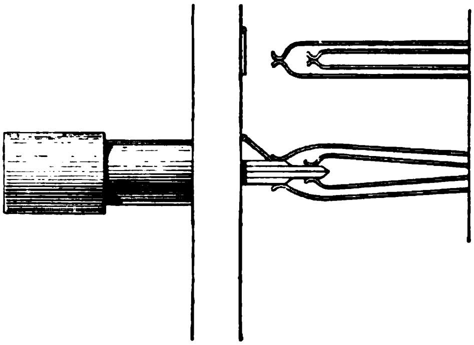


FIG. 891.—TESTJACK AND PLUG.

This plug is formed of four insulated brass strips so arranged that each strip makes contact with one of the jack springs, breaking the line at this point and connecting it by means of a four-way flexible cord to the testing officer's set. For testing purposes a galvanometer, battery and set of connecting keys are usually provided, by means of which current or earth can be connected to the line under test through the test plug; and such faults as earth, disconnections and contacts, can be easily and quickly localised, either toward the exchange or the subscriber's part of the circuit. In conjunction with the test set a telephone instrument is used, and a switch is provided, by means of which the testing apparatus can be connected either to the exchange wiring or to the outside cable bars. A third position of the switch connects the subscriber's line through to the exchange with the testing instrument to bridge across it. Such a set as this cannot, of course, be used for delicate tests such as insulation, capacity or conductor resistance. For these some form of Wheatstone bridge is generally employed, but for ordinary rough tests on short lines where it is seldom necessary to do more than localise the fault to either the outside or the inside part of the circuit, a test set such as that just described is perfectly satisfactory.

It will be evident that an outside cable carries subscribers' lines without any reference to their numerical order, the cable wires are therefore brought on to the cable bars in any convenient order. To connect a line from the cable bar to its proper testjack necessitates a cross-connecting wire; again, the subscribers' lines, in order that the operator's work may be equalised, cannot terminate in numerical order on the local sections. A distribution board is therefore provided, consisting usually of two parallel frameworks of iron carrying distributing strips of vulcanite, or other insulating material, having fixed tranversely brass connecting tabs. Each strip takes twenty lines, those strips on one side of the frame being permanently wired by means of cables to the testjacks and the multiple, and those on the other side being cabled to the local jacks and signalling apparatus; the arrangement is shown diagrammatically in Fig. 892.

The cross connecting must be done in some orderly way; this is usually accomplished by fitting between the frame carrying the cable bars and that carrying the testjacks, and at a sufficient height to allow access to the back of the jacks, wire grids, through the interstices of which the wires from bar to jack are carried in some pre-arranged order.

CENTRAL BATTERY SYSTEMS.

The various central battery systems in use to-day are the outcome of a desire to centralise the necessary sources of energy. This has many advantages ; batteries and generators at subscribers' offices (the latter being the most expensive part of the subscriber's installation) are done away with, and these alone represent a very large saving in the cost of installation and maintenance. The electrical efficiency is also much greater than that of a system with a number of small batteries ; and the central battery, composed of accumulators, can be maintained in good condition. On the other hand the apparatus at the exchange is of a more costly nature than in magneto systems, and the installation of a power plant is necessary.

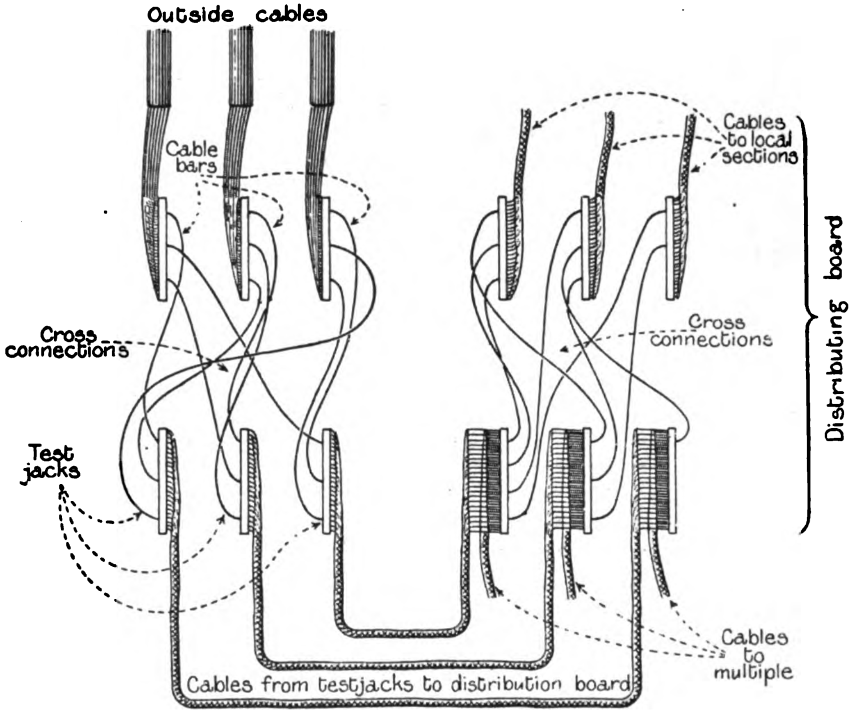


FIG. 892.—CABLE CONNECTIONS FROM POINT OF ENTRY.

The central battery system in general use in this country is a modification of that of Hayes. Fig. 893 shows the complete cord circuit of this system (with the exception of the speaking and ringing-keys). In the cord circuit will be seen the four windings of the repeating coils C, C_1, c and c_1. The coils C and c are wound upon one iron core, and C_1 and c_1 upon another. These coils form practically "one-to-one" transformers which reproduce inductively in the one circuit the current variations produced by speech in the other. In the wires leading from these coils to the ring or "B" line of the plugs are inserted the relays A and A_1 ; the wires from the other pair of repeating coils are connected direct to the tip or "A" line of the plugs. The sleeve or test circuits of the plugs are connected normally to battery through the tongues of the relays B and B_1 and the supervisory lamps D and D_1; these lamps are used to give the ring-off signal, both being extinguished when the subscribers are through to each other and talking, but alight when the conversation is finished and the subscribers have hung up their receivers (*see* page 909). To the plug sleeves are also connected the relays, B and B_1, their other connections going to the contacts of the relays, A and A_1, the tongues of these relays being connected to the wires leading from the battery to the supervisory lamps. The actions are as follow: on the subscriber taking his receiver from the hook his lamp lights up; the operator pushes over her speaking-key, and inserts the back plug into the subscriber's home section jack; battery current will now flow through one side of the repeating coil, and relay A to subscriber; back through repeating coil to battery; this energises A and connects battery through tongue and contact of A and relay B to sleeve of plug, through bush of home-section jack and subscriber's line, cut-off relay G to earth, energising G and extinguishing the subscriber's line lamp; the supervisory lamp D will also be extinguished, being disconnected by the action of B. The operator calls the number wanted by inserting the calling plug in the multiple jacks and ringing; owing to there being a condenser in circuit, until the receiver is lifted there will be no path for the battery current over the line, in consequence the relay A_1 will not be energised. Current will therefore flow from the battery through supervisory lamp D_1, tongue and contact of relay B_1, sleeve of calling plug, bush of wanted subscriber's multiple jack, and through his cut-off relay to earth. The lamp D will therefore remain alight till the subscriber answers, when it will be extinguished because current will then flow through A_1, energising it, and in turn actuating B_1.

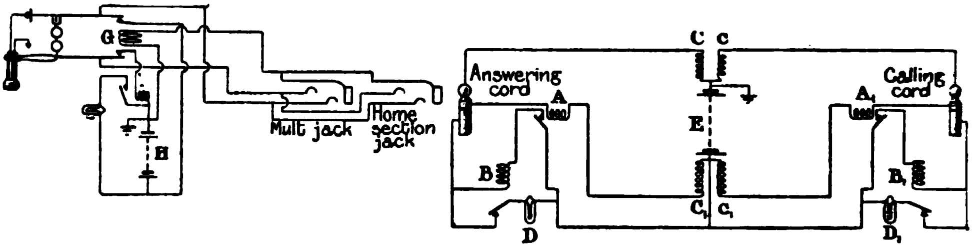
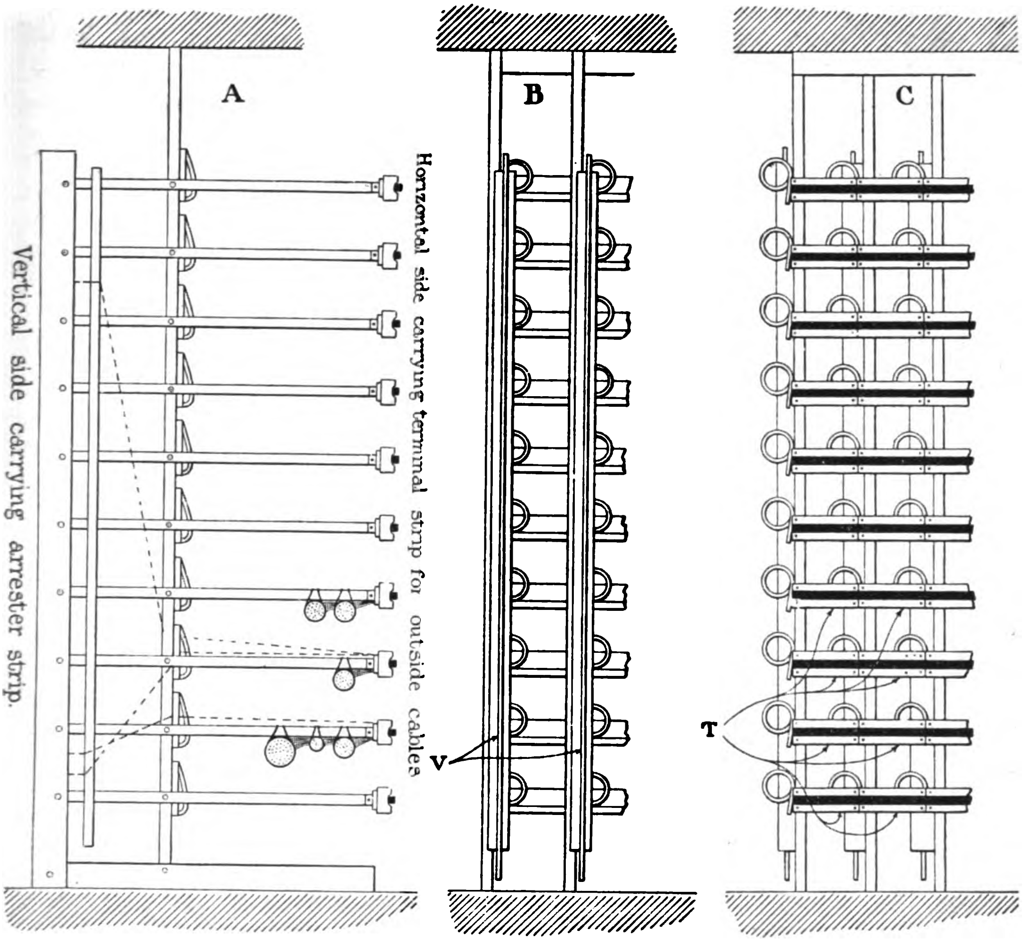


FIG. 893.—CENTRAL BATTERY CONNECTIONS.

The almost universally adopted system of common battery working in this country, and the one used by the General Post Office, is that of the Western Electric Company, which has been evolved from Hayes' system, just described. Testjacks have been done away with—except in the case of a few special circuits, such as call wires, which require frequent testing—as have also cable bars, and in their place we now have the main frame with its "vertical" and "horizontal" sides; this is shown in Fig. 894, A giving a cross section showing the construction. In its essential parts the frame consists of a number of vertical iron strips fastened both to the floor and ceiling, each carrying ten or more horizontal cross pieces. On the "vertical" side of the frame the horizontal bars are fastened to a long iron bar which carries the combined heat coils and lightning arresters, and on the horizontal side terminate in brass castings, to which they are fastened by screws. B gives an elevation of the vertical side, V being the iron bar just referred to, while C shows in elevation the horizontal side and the brass castings already referred to, on which are fitted wooden blocks A (shown in plan and elevation in Fig. 895), which in turn carry a centre composed of two pieces of vulcanite B, between which are clamped brass tabs T, each having three points to which wires can be soldered; each block has forty of these tabs taking twenty subscribers' lines.


A
B
C
Vertical side carrying arrester strip.
Horizontal side carrying terminal strip for outside cables
V
T

Section across end of frame

Front view Vertical side.

Front view Horizontal side.

FIG. 894.—CABLE FRAMES.

We will now trace the course of a line as far as its connections on the main frame are concerned. The outside cables are brought straight in and tied to the undersides of the horizontal cross pieces, the wires being laced out and soldered to one of the points on the brass tabs just described. In Fig. 894 sections of several cables will be seen. The horizontal side of the frame takes the place of the cable bar of Fig. 892 and the vertical side that of the testjack. The paths of three cross connections are shown passing from the horizontal side, through the vulcanite covered rings fitted to the frame to keep the cross connections orderly, over to the vertical side, where they are soldered to the inside springs of the combined heat coils and arresters. The details of one of these is shown in Fig. 896 : V is a section of the bar shown under the same letter in B, Fig. 894 ; A, A_1, B and B_1 are German silver springs, C and C_1 are heat coils by means of which A and B and A_1 and B_1 are connected together. These heat coils are so constructed that any current over a certain value flowing through them melts a small piece of fusible metal, allowing the outside springs to press the springs S, by means of the connecting pins in the heat coils against the plate P, which is connected to earth, thus putting a dead earth on the subscribers' line. K, K, K_1 and K_1 are carbon plates constituting the lightning arrester portion of the apparatus. From the outside springs of the heat coils the wire is carried in cable to the horizontal side of the intermediate distribution frame. This frame is somewhat similar in construction to the main frame; the tabs to which the wires are soldered are, however, different; they consist of a wooden base carrying on the horizontal side of the frame four vulcanite strips, between which are clamped twenty sets of three brass tabs each (Fig. 897). To the outer pair, on the under side are soldered the A and B wires from the heat coils, and the A, B and test wires from the multiple, the upper ends of the tabs are used for the cross-connecting wires. On the vertical side each strip carries twenty sets of four tabs each, these being used for the A, B and test wires to the local jack, while the fourth tab is used for a connection to the subscriber's signalling lamp. The A and B connections to the springs of the cut-off relay are also made on these tabs, as is the test connection through the cut-off relay to earth.

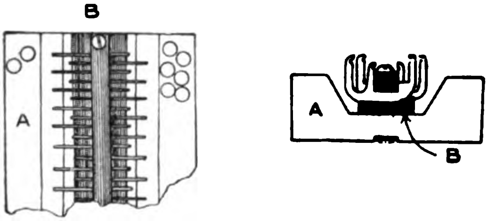


FIG. 895.—TERMINAL TABS.

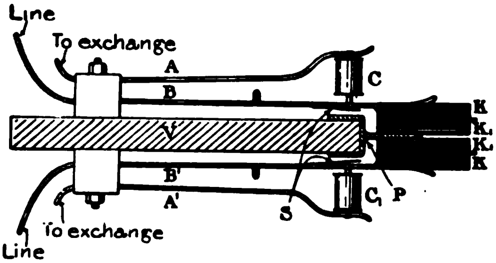


FIG. 896.—HEAT COIL AND ARRESTER.

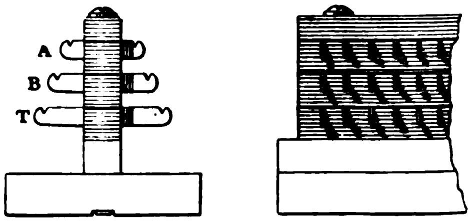


FIG. 897.—INTERMEDIATE TABS.

The complete subscriber's circuit is shown in Fig. 898. Here we see the line coming through the main and intermediate frames, the cross connections in both cases being shown by dotted lines. From the tabs on the vertical side of the intermediate frame, three wires "tee" off to the local section jack and three more to the answering equipment. Of these the A line goes through the 60-ohm line relay A and the two upper springs of the cut-off relay B, to the positive side of the battery, which is also connected to earth; the B line passes through the two lower springs of B and a 60-ohm resistance lamp to the negative side of the battery. The third tab on the vertical side is connected to one side of the coil of B, the resistance of which is 30 ohms, the other side of the coil going to earth. One side of the subscriber's calling lamp, which is shown in the diagram immediately under the local jack, is connected to the fourth or lamp tab on the vertical side of the intermediate frame, from which a second wire is led to the contact of line relay A, the tongue or armature of this relay going to earth on the positive end of the battery. The other side of the calling lamp is connected through a low resistance relay, whose function it is to light the pilot lamp, to the negative side of the battery. The battery is connected to the contact of this relay, while its tongue is connected to the auxiliary or pilot lamp. The other side of this lamp is connected to earth through a relay which operates the night-bell circuit. Across the terminals of this relay is connected some form of two-way switch by means of which the relay can be short circuited out during the day.

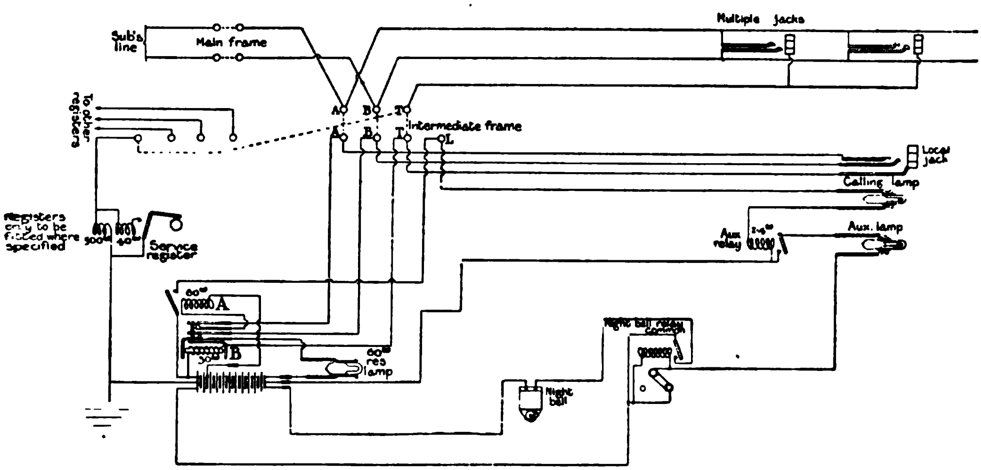


FIG. 898.—COMPLETE SUBSCRIBER'S CIRCUIT CENTRAL BATTERY SYSTEM.

The line and cut-off relays are mounted together on a single base; these are shown in Fig. 899, in the lower part of which the cut-off relay is shown separated so that its action may be seen. The connections at the subscriber's instrument are so arranged that on his removing his

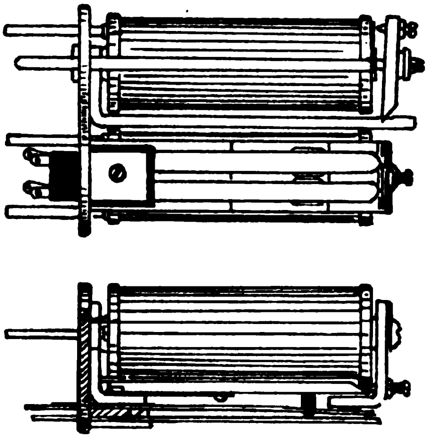


FIG. 899.—LINE AND CUT-OFF RELAYS.

receiver from the rest, his transmitter and the primary of his induction coil are connected across the line. This gives a circuit for current from the battery through the upper springs of B, the line relay, one side of line, primary circuit and other side of line, lower springs of B and 60-ohm resistance lamp back to battery. This circuit, it will be observed, is practically the same as that previously described under central battery systems. A will now be actuated, causing current to flow through its tongue and contact to tab L on vertical side of intermediate frame, and thence through the calling lamp and pilot, or auxiliary, relay back to battery. This relay will now be actuated also, and current will flow through its tongue and contact, auxiliary lamp, and, if it be daytime, through the contact of the two-way switch to battery. Should it, however, be night, this switch would be in the "off" position, and current would flow through the night-bell relay, actuating it and completing a circuit for the night bell. Before dealing further with subscriber's line circuit, it will be necessary to describe that of the operator's cords and speaking keys. This is shown in Fig. 900, and it will be observed is very similar to that of Hayes (*see* Fig. 893). There are however, several important differences, for instance, the extinguishing of the clearing lamps, which in Hayes' system was accomplished by disconnecting the lamp current, is now effected by shunting the lamp with a 40-ohm resistance.

To answer a subscriber the operator takes one of the seventeen pairs of cords before her and inserts the plug of the answering cord into the subscriber's local section jack, which is placed as already described, immediately above his calling lamp. Current will now flow from the battery X through the 40-ohm winding of the repeating coil connected to the B line of the cord, over the line, through the instrument, and back through the A line and clearing relay, and other winding of the repeating coil to battery, actuating this relay. Current will also flow through the 83·5-ohm resistance, the clearing lamp, and the 40-ohm resistance, which is now in parallel with the lamp, and shunts it, preventing it glowing. Hence through the bush of the local section jack to earth through the cut-off relay B, Fig. 898, actuating this relay

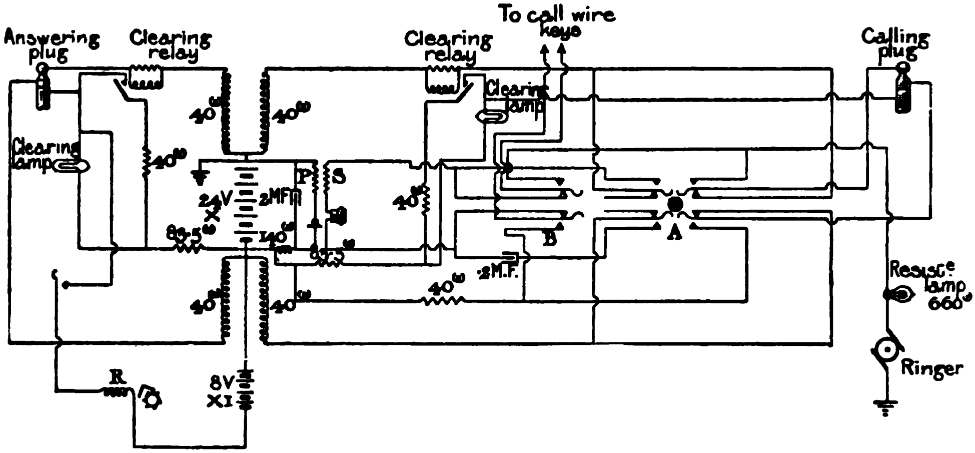


FIG. 900.—DIAGRAM OF COMPLETE CENTRAL BATTERY SYSTEM.

and extinguishing the subscriber's calling lamp by cutting the current off the line relay A, and allowing its armature to fall back. The operator now pushes over the lever controlling the combined ringing and speaking key (A, Fig. 900) associated with the pair of cords she is using, to the speaking side; thus putting her receiver in circuit with the cords. Having obtained the number required by the caller, she tests it in the manner already described in the present chapter, and should the line be clear, inserts the calling plug and rings by pushing the lever of A over to the ringing side. This connects the ringing current from the generator, one side of which is earthed, through one of the outside springs on the right-hand side of A, through the subscriber's line and bell, and back through the other outside spring on the right of A, through a 40-ohm resistance to earth through battery X. When the called subscriber answers, the action of lifting his receiver cuts out the condenser in his bell circuit, giving a loop to the exchange and allowing current from the central battery to flow out over his line and actuate the clearing relay of the calling cord, shunting out the clearing lamp. The cut-off relay of the called subscriber's line will also be actuated; his calling lamp will not therefore glow.

The actual method by means of which the operator gets the engaged test is interesting and novel. When the speaking key is put over, the condenser (which will be seen inserted in the operator's receiver circuit) is connected in series with the operator's receiver across the A and B lines of the calling plug. That side of it therefore away from the receiver will be charged up to a potential of 24 volts by the battery, while the side of it on which the receiver is connected will be at the same potential as the earthed side of the battery, being connected to it through the A line. The bushes of the subscribers' lines will be at the same potential if the line is not engaged, being also connected to earth, and if now tested by the operator no click will be heard. Should a line, however, be engaged there will be current on the bushes of the jacks derived from the third conductor of the cord, and they will therefore be at a higher potential than that of the earthed side of the battery. Now, when an operator tests such a line, her condenser will be partially discharged and a click will be received. Referring again to Fig. 900, it will be seen that the current from the central battery is fed out to the operator's transmitter through a 140 ohm resistance, and also that a condenser is connected across the transmitter. The secondary circuit, with the exception of the method of obtaining the engaged test just described, is similar in all essential features to those referred to when dealing with magneto switchboards.

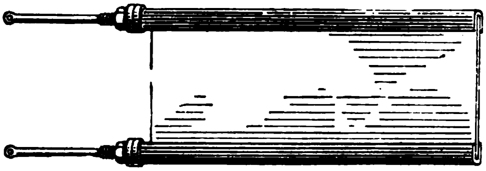


FIG. 901.—SPECIAL RESISTANCE.

The key B is used for ringing on call wires, and becomes necessary in connection with junction working.

The clearing relays in the cord circuits are similar in appearance to the line relay shown in Fig. 899; as they are, however, highly inductive, and in consequence would have an injurious effect on the rapidly fluctuating speaking currents, they are fitted with a second winding in the form of a non-inductive shunt. The 83·5-ohm resistance in the third conductor circuit of the cords is used to cut down the voltage for the clearing lamps, which are designed to work at twelve volts, the battery voltage being twenty-four; these and also the 40-ohm resistances are as shown in Fig. 901.

Each operator's position is fitted with a counting machine or meter, shown at R in Fig. 900, and in greater detail in Fig. 902; it consists of an electromagnet, to the armature of which is pivoted a lever whose end engages with a ratchet wheel moving a train of wheels similar to a cyclometer. Every time the armature is pulled up it moves the ratchet wheel on one tooth. These meters are so designed and adjusted that they will not work at a potential lower than thirty volts. This extra potential is supplied by means of a small subsidiary battery shown at x_1. A key is fitted in connection with each pair of cords on the operator's positions; the depressing of this connects x and x_1, in series with each other through the meter and to earth, through the bush of that subscriber's jack in which the answering plug is inserted; the meters therefore cannot be actuated unless a plug is in a jack. Each meter is provided with a contact which, when the armature is pulled up, completes a circuit for a lamp placed on the operator's position, the glowing of which serves as a check and also shows the operator whether or not the meter is working correctly. The meter shown in Fig. 898, and connected to the test tab on the horizontal side of the intermediate distribution frame, is for the purpose of recording the calls made by the subscriber; it is identical in construction and action with the operator's meter just described, and is operated by the depressing of the operator's meter key. In Fig. 898 there will also be noticed a 60-ohm resistance lamp connected between the negative

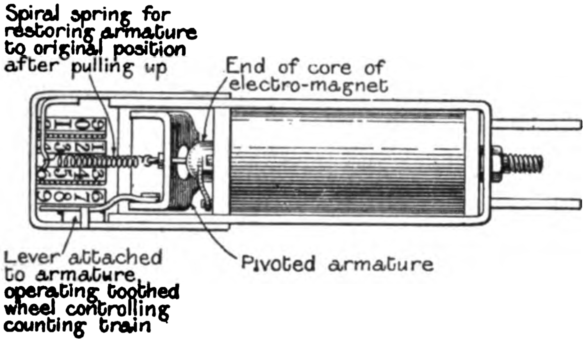

Spiral spring for restoring armature to original position after pulling up
End of core of electro-magnet
Lever attached to armature operating toothed wheel controlling counting train
Pivoted armature

FIG. 902.—CALL METER.

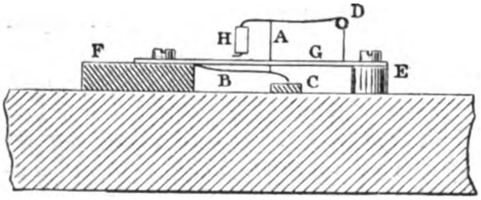


FIG. 903.—ALARM FUSE.

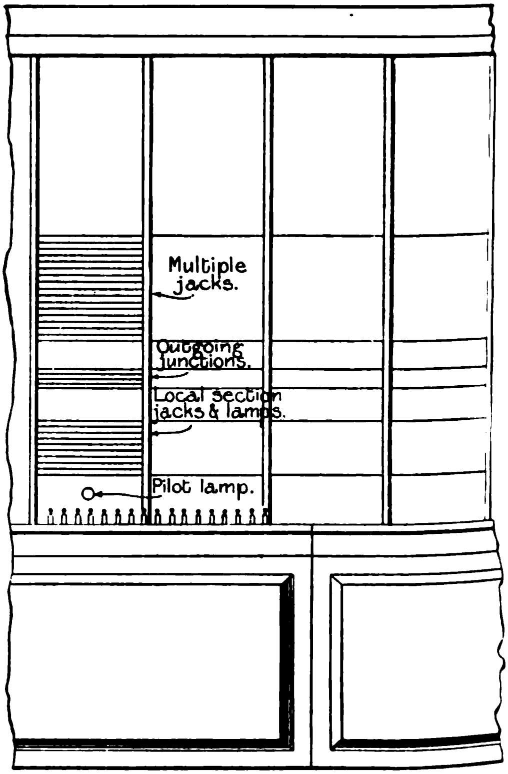


FIG. 904.—ARRANGEMENT OF JACKS.

side of the battery, and the B line, this serves to show up earth faults, and one such lamp is inserted in each line. Fuses are inserted between the battery and every circuit fed from it, the latest pattern of these is a combined fuse and alarm, and is shown in Fig. 903. G is a micanite base supporting a vertical piece carrying at its top the spiral spring D, one end of which is extended and carries at its end the glass bead H. F is the negative busbar, and from it current flows through the spring B, fuse A, and spiral spring D to E, to which the wiring of the circuit is connected. Should sufficient current flow to fuse A the spring B will make contact with bar C, to which is connected an ordinary trembling bell, and the tension of D will pull up the extension, carrying H to a vertical position, thus showing which fuse has blown.

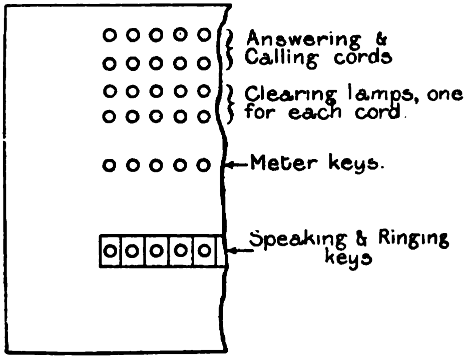


FIG. 905.—KEYBOARD ARRANGEMENT.

The general arrangement of local, multiple and outgoing junction jacks is shown in Fig. 904, the function of these latter jacks will be explained later. Fig. 905 shows in plan part of the keyboard arrangement. The combined speaking and ringing key is shown in Fig. 906, which gives a side and an end view; it consists of twelve German silver springs mounted on pieces of vulcanite screwed on to a metal base. A cam lever is fitted carrying on its lower end a vulcanite barrel which, on the lever being moved to one side or the other, forces the springs into or out of contact with each other.

MISCELLANEOUS EXCHANGE SYSTEMS.

THE DIVIDED BOARD.

This is one of several systems designed with the intention of doing away with or minimising the tremendous amount of multiple required in big exchanges built on the multiple system. At present the limit of size of the multiple board is about 20,000 lines, and for anything over this some special arrangements must be made.

In a divided board these comprise the dividing of the multiple into two or more parts according to its size; thus in an exchange of 30,000 lines the multiple for the first 15,000 lines would form one division, and that for the second 15,000 another division of the board. Each subscriber has two or more means of calling the exchange according to the number of divisions of the board, and in consequence each division has an answering jack and indicator for every subscriber, but a multiple only of those numbers allotted to that particular division. When a subscriber requires to be connected to a number in the first 15,000, he operates his calling signal situated on the division of the board carrying the multiple jack of that number. This type of board certainly results in a large saving of multiple jacks, but this economy is somewhat counter-

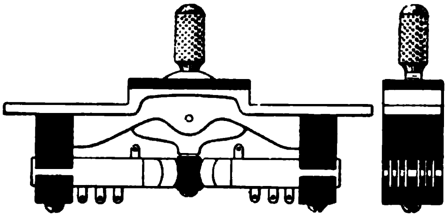


FIG. 906.—COMBINED KEY.

balanced by the fact that two or more sets of signalling apparatus are required for each subscriber, and also that, small as is the amount of thought required on the part of the subscriber, mistakes are frequently made by them, and result in a large amount of extra and unnecessary work being thrown on the shoulders of the operators.

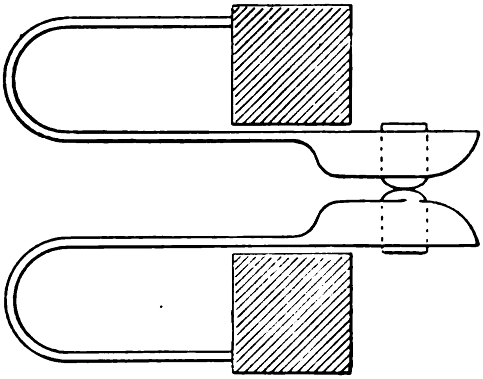


FIG. 907.—P.O. SUBSCRIBER'S JACK.

The General Post Office has introduced into several towns where they have established telephone exchanges, a system which possesses many features of interest. One of its characteristics is that a current is always flowing over the lines when they are not being used for speaking; this among other things serves as a permanent test of the condition of the line.

Fig. 907 shows one of the subscriber's jacks at the exchange. It consists of two brass springs, whose ends carry ebonite distance pieces. The plug used to make the necessary connections is shown in Fig. 908. A and B are two flat brass strips insulated from each other by a piece of vulcanite. Fig. 909 shows the subscriber's indicator; it consists of a pair of electro-magnets A A mounted on a brass ring. C is a soft iron ring, pivoted in such a manner that it tends to fall away from the poles of A A, and is only held up against them by means of the current flowing over the line; on the front of C is engraved the subscriber's number. E is a small magnetic needle suspended between the magnet poles; normally this points to the left. If a subscriber takes his receiver off the rest, this disconnects his battery from the line; A A therefore become demagnetised, allowing E to drop to a vertical position, and the ring C to fall forward. D is an insulated stud mounted on the pillar, carrying C, and having attached to it a light spring G which is pressed against the pin D when C drops and thus completes the local circuit of a night bell connected to D and D′.

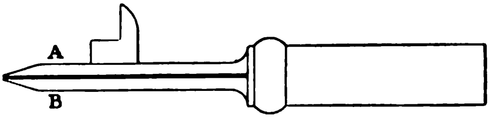


FIG. 908.—PLUG FOR P.O. JACK.

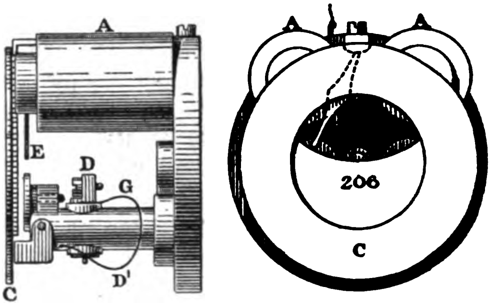


FIG. 909.—P.O. INDICATOR.

The following is the method of operating: When a subscriber rings up, the operator connects her instrument first to the caller and then to the called number by a plug, and then connects them by a double-ended cord. When the subscribers replace their receivers their batteries operate their indicators, both of which are permanently connected in bridge or leak. The means by which the calling of a subscriber is effected is interesting: the current flowing to line from the subscriber's office, passes through a relay fitted in his instrument, the armature of which is biassed so as not to be operated by the current: the operator connects the calling current to his line, and this, flowing in the same direction as the permanent current, so strengthens it as to overcome the bias of the relay which, pulling up, closes the local circuit of a bell and battery. Fig. 910 shows two subscribers A and B connected, while D has just rung up and is being answered.

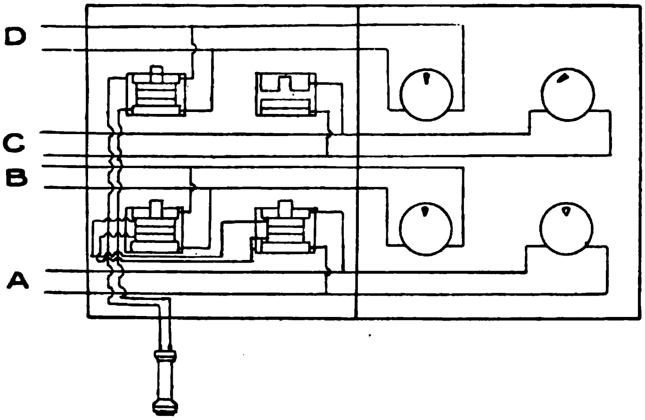


FIG. 910.—P.O. SWITCHBOARD CIRCUITS.

A top view of the relay used is shown in Fig. 911. A is the armature pivoted between the coils and carrying a projecting piece T, on each side of which is a platinum contact piece. A is normally held in the position shown by the tension of the spring S; on a sufficiently strong current being passed through M M, their attraction pulls A toward them against the tension of S, breaking T away from *b* and causing it to make contact against C, and completing the bell circuit, one side of which is connected to T and the other to C.

At Newcastle, where the G.P.O. has a large exchange, the above system has been amplified and arranged for multiple work, many improvements having been made; while the permanent current has been retained, the jacks, plugs, and subscribers' indicators are of somewhat different design to those just described.

CALL-WIRE SYSTEMS.

These have not been much used in England, and are now quite obsolete; they consisted in having a line, called the *call wire*, terminating on an operator's headgear receiver at the exchange, and brought through every subscriber's office. To this call wire and the operator any subscriber could connect himself by depressing a key fitted to his instrument; in addition to the call wire he was supplied with an exchange line of his own.

There are two methods of connecting call wires, either all the subscribers can be connected to one main call wire which is carried to each instrument, or branches may be taken from the wire as in the Mann system. In the Law system a single disconnection will break down the whole call wire, such a disconnection on the Mann circuit may only affect a few subscribers. Mann's system was further improved by Mr. J. D. Miller, who con-

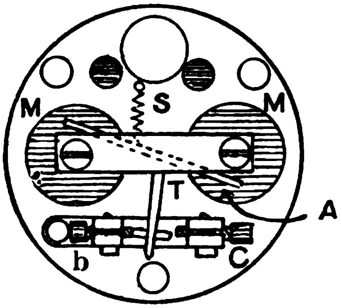


FIG. 911.—P.O. RELAY.

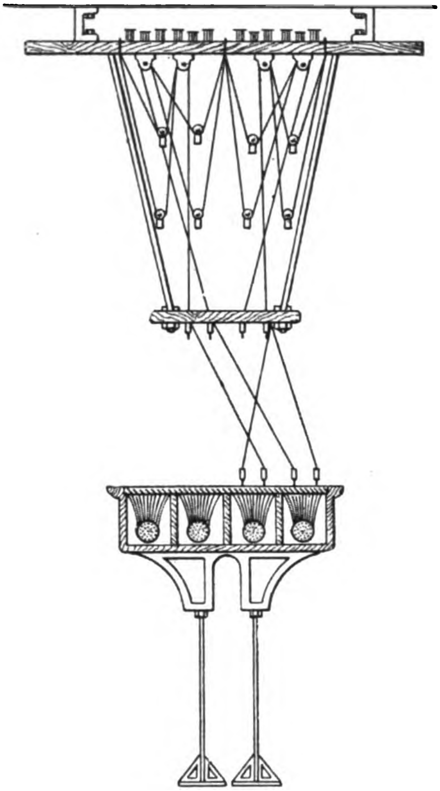


FIG. 912.—FLAT BOARD (SECTION).

secondary circuit. The subscribers' lines came on to jacks, multipled round the board, which, contrary to usual practice, was horizontal, in the form of a table, on each side of which an operator sat. This resulted in saving half the multiple required for a vertical board of the same capacity. The connecting cords and plugs were suspended from a canopy above the table as shown in Fig. 912. Fig. 913 gives the connections of a pair of cords and engaged test circuit and shows two subscribers connected together.

B is a testing thimble worn by the operator and connected through a relay as shown. There is one relay for each operator, connected to one terminal of the operator's receiver. If now the operator taps the tip of her thimble on the bush of an engaged line, the ten-cell battery, through the relay, pulls up the relay and completes the local circuit for the testing battery through the operator's receiver, giving a click in the receiver.

It should be remembered that although not shown in Fig. 913 the call wire is also connected to the operator's receiver. For the purpose of receiving calls at night nected the call wire as a metallic loop ; so that one disconnection did not affect the service at all.

In Manchester Messrs. Bennett and Maclean introduced a system which was very successful. In it the depressing of the call wire key disconnected the subscriber's instrument from his line, connecting him to the call wire and at the same time putting an earth on his

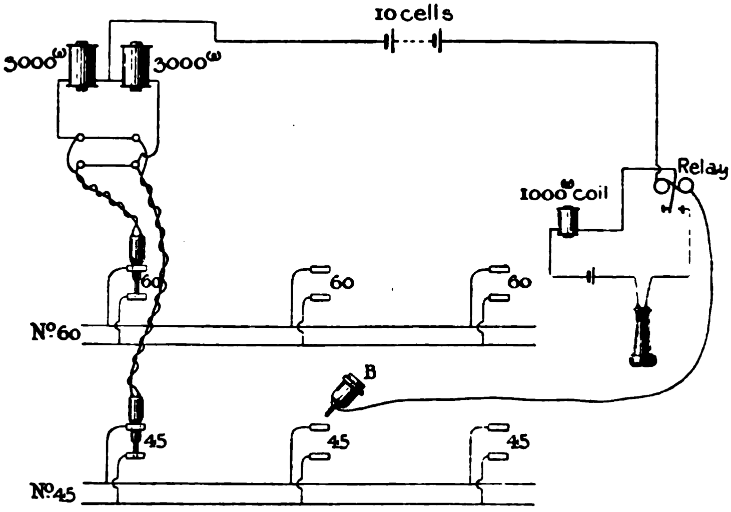


FIG. 913.—CALL WIRE ENGAGED TEST.

an indicator is operated by a subscriber coming on to the line and, falling, closes the circuit of a night bell and battery.

CALLING BY MEANS OF LAMPS.

It is becoming more and more the practice to use small incandescent lamps in the exchange instead of indicators. They are simpler, cheaper, and more compact, and attract the operator's attention with greater certainty. Fig. 914 shows a type of lamp commonly used, and made to work at various voltages from four to twenty-eight volts. Immediately above each strip of lamps is fitted the strip of local or home-section jacks so that when any lamp glows, the operator has only to plug into the jack above it to answer the call; this means a considerable saving of time.

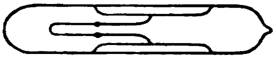


FIG. 914.—CALL LAMP.

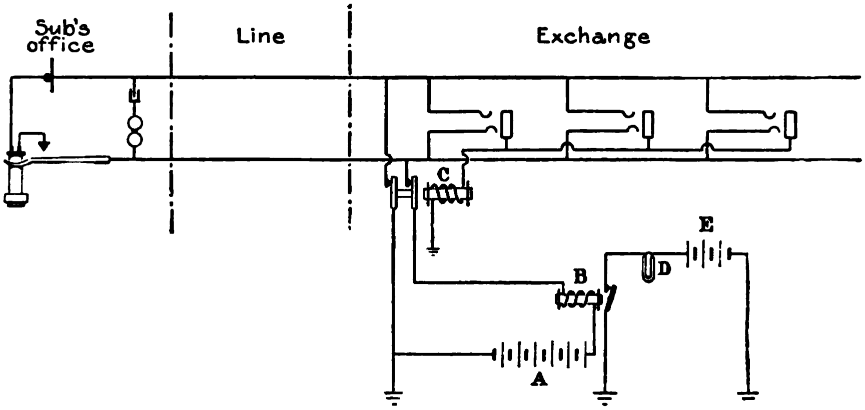


FIG. 915.—CIRCUITS FOR LAMP CALL.

The connections of a subscriber's line are shown in Fig. 915, all the apparatus to the right of the vertical dotted line being in the exchange. At the subscriber's office a condenser of about ·75 microfarad is fitted in series with his magneto bell; the effect of this is to stop the flow of current from battery A while the receiver is on the hook, while it allows the alternating calling current from the exchange to pass and operate the subscriber's bell. When the subscriber removes his receiver from the hook, the earthed battery A sends current through relay B, one contact of relay C, through subscriber's circuit and second spring of C to earth. This operates B, completing the circuit of the signalling lamp, D, from one side of battery E, through D to earth at armature of B. On the operator plugging in to answer the call, the current which is connected to the barrel or third conductor of the cords, flows through the bush of the home-section jack and relay C to earth; this relay disconnects the battery A from the subscriber's line allows the armature of B to fall back, and the line lamp goes out.

Each panel of lamps is usually fed from one fuse by means of a common wire, and on the panel is fitted a lamp known as a pilot lamp, the more certainly to attract the operator's attention.

CHAPTER III.—LINE CONSTRUCTION.

OVERHEAD AND UNDERGROUND CABLES—WOOD AND IRON POLES—ERECTING POLES—OVERHOUSE WORK.

CABLE DISTRIBUTION.

THIS branch of telephone engineering is carried out under two systems: one, the original, being by means of overhead wires and cables, and the other by cables laid underground, the latter method being now used principally in the larger towns. In the overhead system bare wires of hard drawn copper or phosphor bronze, strung upon insulators fitted on poles or house-tops, are used to connect up to local subscribers, or from the subscribers' premises to a cable connecting box placed at a convenient point within the area to be served; from this point an insulated cable hung by suspenders from a supporting wire, is taken to the derrick on the top of the exchange. From the derrick cables are run down into the exchange, terminating at what is called the main frame—the further course of the wires will be found dealt with in the chapter relating to exchanges.

This system, while much cheaper than the undergrcund in the first instance, is subject to troubles which materially affect the efficient working of the service, not the least of which being loose joints. Apart from this fault and others arising from leakage, etc., heavy storms, premises on fire, and similar causes, have frequently resulted in causing temporary, but entire, dislocation of the service in certain areas.

POLES.

Originally only wood poles were used, preferably larch with oak arms, but the later practice is to use wrought iron tubular poles, either in a single length or in sections telescoped together. Fig. 916, A, shows such a pole, and Fig. 916, B, a light tapered one such as is occasionally used for single lines.

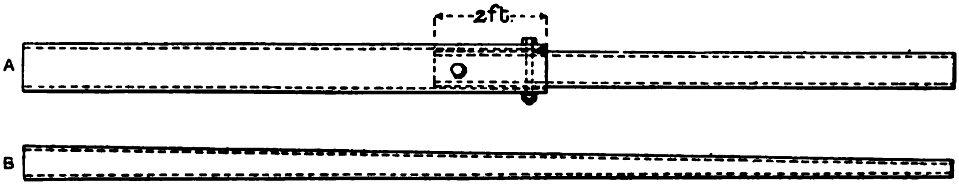


FIG. 916.—WROUGHT IRON POLES.

The depth at which a pole should be set depends a great deal upon the nature of the soil. A good solid foundation should be obtained, and it is always advisable to ram large stones, or other solid material against the butt of the pole.

The following table gives the approximate depth at which poles should be set; but, briefly stated, the depth should never be less than 4 feet for a 24 foot pole, with 1 in. extra depth for each additional foot in the total length of pole.

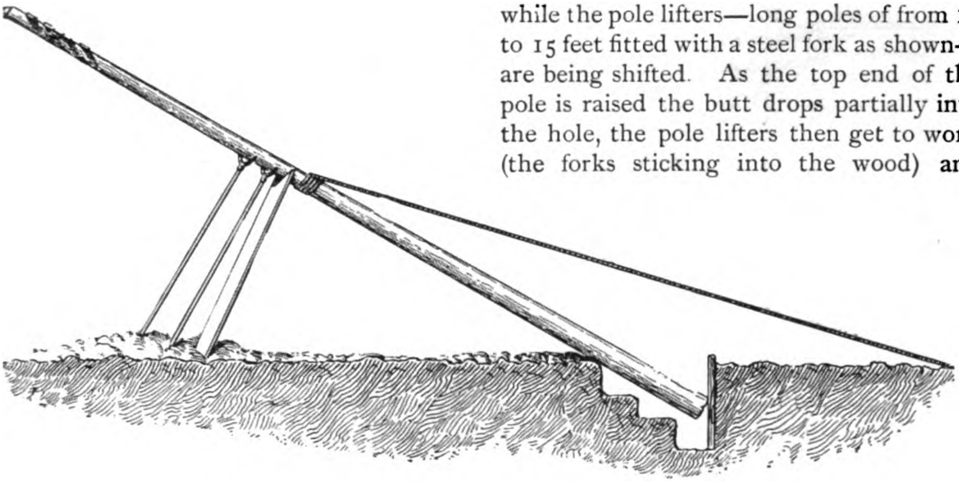


FIG. 917.—RAISING A POLE.

Table of depths for setting poles.

24 foot	pole	set	4 feet deep.
30 foot	„	„	4 feet 6 in. deep.
36 foot	„	„	5 feet deep.
42 foot	„	„	5 feet 6in. deep.
48 foot	„	„	6 feet deep.

ERECTING POLES.

The general practice is to dig a hole about 5 feet long (in the direction of the line when possible) and a trifle wider than the butt of the pole. This hole is stepped, as shown in Fig. 917, and the pole placed over it. Pole raising boards and pole lifters are used, the former having a semi-circular shaped end to receive and steady the pole while the pole lifters—long poles of from 12 to 15 feet fitted with a steel fork as shown—are being shifted. As the top end of the pole is raised the butt drops partially into the hole, the pole lifters then get to work (the forks sticking into the wood) and the pole is raised high enough to allow the raising board to take the weight while the lifters take up a fresh position. When the pole is erect ramming and filling in complete the operation. Very heavy poles cannot be raised thus, but a derrick and rope tackle are employed, as shown in Fig. 918. Poles should always be set slightly against the pull of the wires.

All wood poles are treated with some preservative compound, the most enduring

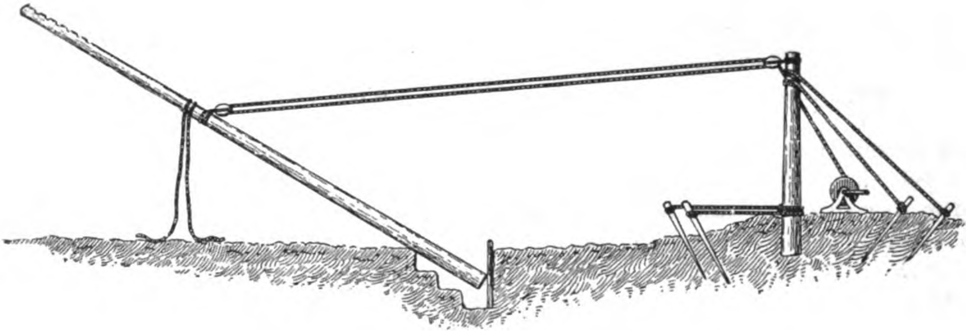


FIG. 918.—DERRICK FOR RAISING POLE.

being creosote; tarring the butt is sometimes resorted to, and should in all cases be carried well above the ground line.

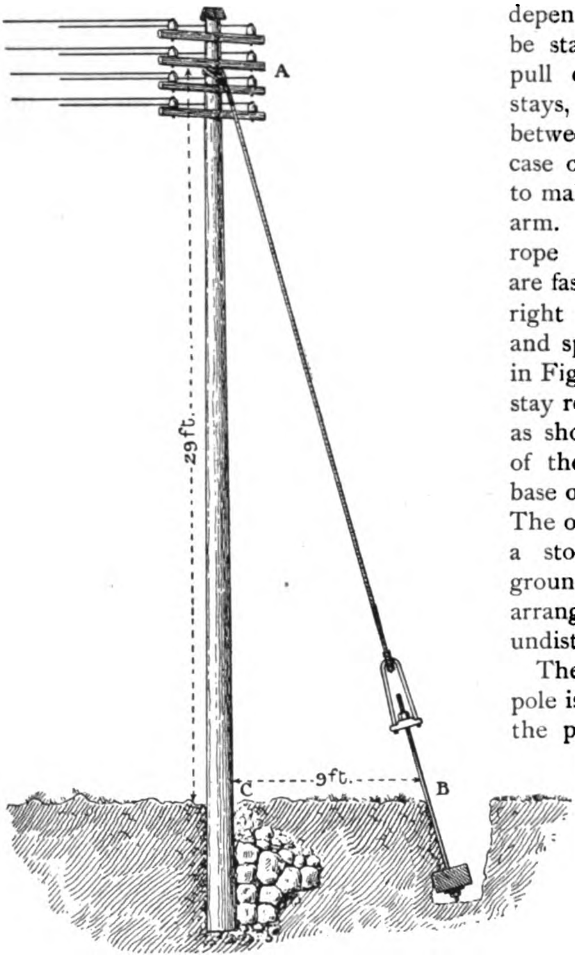


FIG. 919.—POLE SET AND STAYED.

The oak arms used are 2¾ in. square in section, the length varying to suit requirements, and they are checked into the pole at a distance of 12 in. from centre to centre and fastened by a ⅝ in. iron bolt, nut and washer. These arms are interchangeable, the holes in all cases being for ⅝ in. bolts. Insulators are spaced with centres 9 in. apart, which gives a clear space of 18 in. at the pole, thus allowing room at the centre for the lineman to work, the outermost insulator being 3 in. from the end. Generally speaking, poles should not be placed at a greater distance apart than 65 yards, but this distance entirely depends upon the route. All poles must be stayed or strutted to counteract the pull of the wires, and in the case of stays, the fixing point should be halfway between the top and bottom arms, in the case of struts it is found more convenient to make the fixing just below the bottom arm. Stays are made of stranded wire rope ⅝ in. or ⅞ in. in diameter; they are fastened to the pole by taking the rope right round once, bringing down the end and splicing it with binding wire as shown in Fig. 919. The lower end is fastened to a stay rod by means of an eye and thimble, as shown in Fig. 919, the threaded end of the rod B being passed through the base of the thimble and adjusted by a nut. The other end of the rod is passed through a stout baulk of timber sunk in the ground and well rammed; the pull is arranged to come against the solid or undisturbed side of the hole.

The angle the stay makes with the pole is an important factor in determining the pull it will have to withstand. In Fig. 919 a pole 36 feet long is shown set a depth of 5 feet. As there are four arms spaced, as already described, the top of the stay would be fixed 2 feet from the top of the pole, and if the stay enters the ground at a point 9 feet from the base of the pole, we have a right-angled triangle consisting of the pole, ground and stay, two dimensions of which we know; from these it is easy to arrive at the third, 30·3 being the length of the line A B. Having obtained the length of A B, a simple application of the triangle of forces gives us the relation

$$BC : BA :: AW : X,$$

W being the total pull exerted by the eight wires and X representing the ultimate stress which will come on the stay. If we assume that each wire exerts a pull of 300 lbs., we have 8,080 lbs. as the total stress on the stay. On long lines it is necessary to stay one pole every quarter of a mile "fore and aft," that is, one stay on each side of the pole in the direction of the line; the stays in this case should be fixed at the same point on the pole and should each form an equal angle with it. On heavy lines it is desirable to fix additional stays at right angles to the line to counteract wind pressure, and on all poles where the wires form an angle, two stays should be fitted to counteract the different pulls. In some cases it is impossible to fix stays, trussing is then adopted, an illustration of such work being given in Fig. 920. This prevents the pole from bending, but does not prevent its being pulled over.

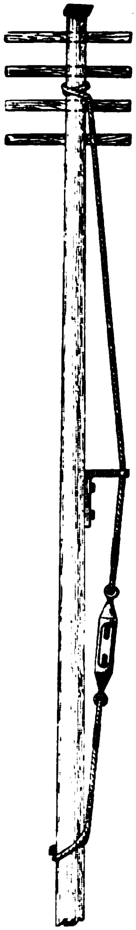


FIG 920.—TRUSS.

Struts are also fitted with a stout piece of timber placed at right angles to the bottom end (a short piece of pole serves the purpose). In fitting struts the pole should never be cut to allow the strut to be checked in, but the top end of the strut should be carefully fitted to the circumference of the pole and the fixing made with a bolt, nut and washer, as shown in Fig. 921. All poles are fitted with a protecting cap of some kind; on country roads, etc., a galvanised iron roof is used, and in towns or suburban areas, turned finials. A stout galvanised iron wire to form a lightning guard, is always carried from a point two or three inches above the top of the pole right down to the butt, terminating in a flat spiral which is tucked in under the butt; this wire should be passed under the washers of the bolts which fasten the arms to the pole, and then stapled straight down.

OVERHOUSE WORK.

Wrought-iron tubular poles are invariably used for this class of work, and can be had in various lengths up to 18 or 20 feet; where a greater length is required two or more are telescoped together. The foot of the pole is set in a cast-iron shoe or chair, as shown in Fig. 922, these shoes being of various shapes to suit the different requirements. The pole, when set into the socket, is wedged up, but

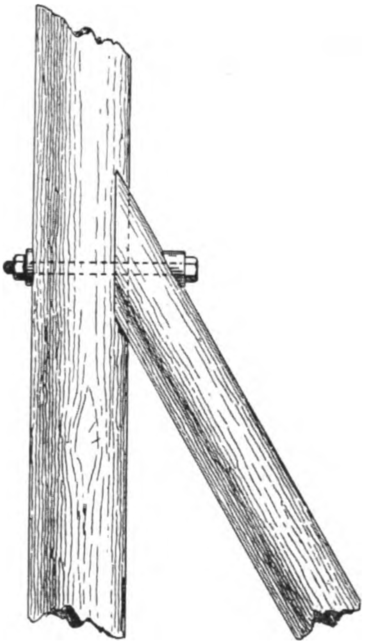


FIG. 921.—STRUT ATTACHMENT.

as there is nothing to prevent the base from moving, the system of staying has to be somewhat elaborate. Short poles should never have less than four stay wires, each fitted with a stay tightener, and where the load is heavy, or long poles are used, eight stays at least should be fitted, four near the top of the pole and four at or about the joint.

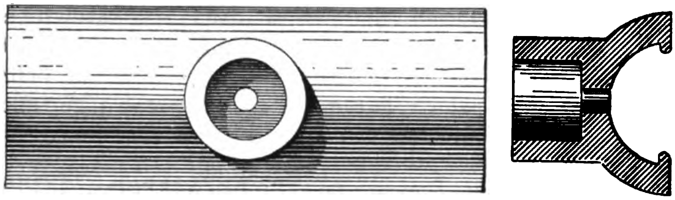
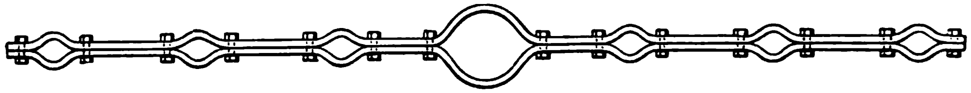


FIG. 922.—RIDGE CHAIR.

Great care is necessary in fixing stays in overhouse work. Copings, parapet walls, and light chimney stacks should never be used for such a purpose; where possible the stay wire should be carried down the outside of the building for some distance and firmly secured to a good eyebolt or strong spike driven into the wall. When the wire passes over the edge of copings, etc., such edges must be protected by a short piece of angle iron, and it is necessary to make sure that the coping will not be pulled over when the strain comes upon it: too many precautions cannot be taken. Where the chimney stacks are heavy enough and sound enough to justify staying to, a length of stay wire should be passed right round the stack and made fast, and the stack must be protected by an angle iron at each corner, the pole stay wire is then attached to the one encircling the stack. Stays can sometimes be fixed to the main timbers of the roof, in which case either a ring bolt or a pivot hook is used. A hole is bored through the timber, a stout piece of sheet lead is then fitted with a corresponding hole, the ring bolt or pivot hook with a good hemp grummet well smeared with white lead and tallow, is then passed through and nutted up with a heavy square washer behind. The pole shoe or chair into which the pole is set has a hole in the bottom to allow for the escape of any water which might find its way in, and to avoid risk of any leakage to the roof it should be set on a piece of stout sheet lead under which several thicknesses of tarred roofing felt are placed. In the fixing of iron arms, climbing clips, etc., to iron poles there are no holes to drill, clamping methods being resorted to throughout. In Fig. 923 is shown an arm. The channel iron of which the arm is made is generally 1¼ in. × ⅝ in., but for heavy work 1½ in. × ¾ in. is used The two halves are fixed together by ⅜ in. iron bolts and nuts.



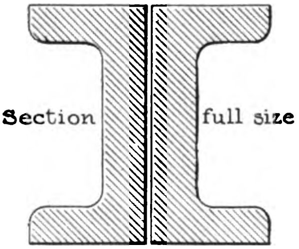


FIG. 923.—IRON ARM WITH SECTION.

INDEX.

A

Accumulator, Acid, 74, 84
—— buckling, 81
——, Capacity of, 68, 70
——, Charging, 77
——, Chemistry of, 67
——, *Chloride*, 93
——, *Crompton-Howell*, 92
——, Definition of, 64
——, Discharging, 68, 69, 77
——, Efficiency of, 76
——, *Epstein*, 93
——, Erection of, 75, 84
——, Formation, 66, 72, 74
——, Gas, 64
——, *Gladstone* and *Tribe* on, 66
—— Hydrometers, 75
——, Insulation of, 76
——, Lead, 65
——, *Lithanode*, 95
——, Pasted plate, 71, 83
——, *Planté's*, 65
——, Resistance of, 68, 82
——, Spray arresters, 83
——, Sulphating, 80
——, The *D.P.*, 73, 91
——, The *E.P.S.*, 83
——, The *Tudor*, 85
——, "Topping up," 76
——, Uses of, 89, 91
——, Voltage of, 67, 68, 78, 79
Acids, table of densities, 136
Action, Local, 39
Acyclic generators, 484
Air ducts, 537, 542
—— gap, 420, 448
Aliment, 38
Allen, *T. S.*, on core losses, 526
Alloys, 15
Alternating current, 355, 417
—— —— circuits, graphical treatment, 367, 372, 377, 379, 388, 390
—— ——, Clock diagrams for, 367, 387
—— ——, Lag of, 363, 365
—— —— machines, Chapter on, 508
—— —— power, 360
—— —— —— factor, 366
—— ——, Virtual value, 385
Alternator compounding, 678
—— testing, 662
Alternators, 416, 508, 516–554
Amalgamation, 39
Ammeter calibration, 333
Amortisseurs, 530
Ampere, 9, 23
——, Definition of, 239
——, meters, 129
—— ——, Hot wire, 276, 278
—— ——, Idle current, 299
—— ——, Induction type, 294
—— ——, *Kelvin* balance, 270
—— ——, Moving iron, 259
—— ——, —— coil, 264
—— turns, 194
Ampere-hour meters, 722
Amyl-Acetate standard, 701
Anions, 16
Anode, 6, 9, 15, 23
—— of supply meter, 732
——, Suspension of, 123
Anodes, Nickel, 123
—— of plating baths, 129
Arago's rotations, 512
Arc lamps, 689
Area of induction motor gap, 592
Armature construction, 430, 475, 492, 500
—— core, 470, 474
—— of overhung alternator, 546
—— reaction, 449, 474
—— resistance, 643
——, Volume of, 466
—— winding, 435, 518
Aron meter, 729
Arresters (*see* Lightning Arresters)
Astatic combinations, 247–8
—— galvanometer, 246
Atkinson-Schattner maximum demand indicator, 723
"Auto-transformer," 598, 716

B

Balance of clock meter, 730
——, *Kelvin*, 270
Balancer, 749, 750
—— in railway working, 820
Balancing by induction motors, 770
Ballistic galvanometers, 251, 310
—— ——, calibration, 313
—— ——, Hints on, 311
—— ——, logarithmic decrement, 253, 313
—— pendulum, 252
Band brakes, 665
Bars in rotor windings, 593
Bastian meter, 733, 781
Baths, plating, 115–117
Bearings, 470, 492
Behrend method of alternator testing, 663
Berry transformer, 558
Bidwell's method of testing iron, 654
Binding of armature conductors, 476
Bobs, Wood to make, 111
Bonding tram rails, 798
Booster, 749
——, *Entz*, 753
—— feeder, 750
——, *Highfield*, 750
——, Reversible, 750
—— series, 749
——, *Turnbull and McLeod* 751
B.O.T. unit, 722
Bow, Tramway, 806
Bracket for tramway, 803
Brake magnet, 724
Brakes for motor testing, 664
—— for supply meters, 724, 728
Brass surfaces, grinding of, 110
Breadth coefficient, 520
Bridge, Wheatstone's, 319
Brighton system of charging, 722
Brown, *C. E. L.*, experiments on rotors, 572
Brush, Carbon, 427, 481, 601
—— friction, 456
—— of dynamos, 417, 434, 474, 490
—— resistance, 643, 645
—— rocker, 474, 477
Brushes, Copper, 452, 478, 481
—— for use in electro-plating, 113 *et seq.*
Brussels, Cost of working trams at, 811
Bunsen cell, 125
——, grease spot photometer, 702
Burnishers for use in electroplating, 121

C

Cable dividing boxes, 778
——, joint boxes, 776
Cables for interior wiring, 705
——, high-tension, 778
——, hygroscopic, 773
——, Jointing, 774, 775
——, —— small, 706
——, Loading of, 705, 706
——, Systems of laying, 773
Calibration of ammeter, 333
—— of ballistic galvanometer, 309, 313, 314
—— of differential galvanometer, 323
—— of galvanometer, 308
—— of slide wire, 325
—— of voltmeter, 328, 329, 330, 331
Calorie, Definition of, 242
Capacity, 11
—— current, 376
—— effect of water resistances, 662
—— in alternating-current circuit, 372
Capital expended for lighting, 722, 723
Carbon brushes for induction motors, 601
—— for brushes, 434
Cardew instrument, 274
Cascade speed regulation, 515
Casting plaster from jelly, 149
—— —— —— plaster, 150
Cast-iron for field system, 429
—— surfaces, Grinding of, 110
Catenary construction, 822
Cathode, 6, 15
Cathode of supply meter, 732
Cations, 16
Cell as a furnace, 35, 39
——, Bichromate, 52
——, *Bunsen*, 125
——, *Carhart-Clark*, 241
——, Change of resistance in, 43
——, *Clark*, 59, 241
——, Classification of, 50
——, *Daniell*, 42, 58, 239, 246
——, Dry, 62
——, *Fleming*, 61, 241
——, *Fuller*, 54
——, *Grove*, 51
——, *Leclanché*, 55
——, —— Agglomerate, 56
——, Qualifications of good, 49
——, Resistance of, 41
——, Secondary, 64
——, *Smee*, 50
——, Standard, 241
——, *Trouvé*, 53
——, Types of, 50
——, *Weston* or Cadmium, 241
Cells, 26
——, E.M.F. of, 29, 41
"C.G.S." system, 237
Characteristic curves, 459
—— of compound machine, 463
—— of series machine, 459
—— of shunt machine, 642
Characteristics, Motor, 639
——, Short circuit, of alternator, 662
Charging for energy, 722
Cheapness in design, 464, 467
Chemical generators, 35
Circuit breakers (*see* Switches)
——, "Closed," 28
——, External, 5
——, "Open," 28
——, "Short," 28, 445
Cleats, Porcelain, 710
Clock meters, 729
Coefficient of leakage, 421, 471
—— of magnetic dispersion, 576, 579, 588
—— of output, 464
—— of utilisation, 576
Cogging of motors, 588, 611
Coils, Cross, 592
——, End, of turbo generators, 549, 552
——, Hand and former wound, 523, 576
—— of transformers, 556, 559
——, Temperature of, 648
Collector bow, 806
—— shoes, 809, 812, 813
Colours, effect on eye, 700, 704
Commutation, 443, 468
—— poles, 447, 467, 479, 493, 507
Commutator, 417, 432, 456, 470, 476, 478, 481
—— key, 306
—— mercury, 306
—— of *Heyland* alternator, 879
—— single-phase motors, 614

Compensating winding in single-phase motor, 616, 618
"Compensators," 715
Compound characteristics, 463
—— motors, 488
—— windings, 428, 458, 474, 484
Compounding of alternators, 678–683
Condenser, 9, 11, 307
Conductors, 4
——, Conductance of, 12
—— in series and in parallel, 24
Conduit of *G.B.* system, 813
—— tramway system, 801, 807–811
——, —— ——, Cost of, 809
Consumption in cell, 35, 37
Contact chamber, 811, 812
—— in testing resistances, 643
—— resistance, 645
—— surface, 801
Continuous current machines, Chapter on, 458
—— —— transformers, 620
—— currents, 417
Converters, Cascade, 629
——, Rotary, 620
Cooling of machines, 549
Copper losses, 453, 456, 637
—— voltameter, 333
Core, Construction of, 474
—— of induction motor, 581, 594
—— of transformers, 554, 558
——, Smooth, 430
Cotton insulation, 423, 425, 649
Coulomb, Definition of, 240
Crane motors, 499
Crompton arc lamp, 691
Cross-magnetisation, 449
Cumulative compound motors, 488
Current, Alternating, 355
—— density in conductors, 434, 457, 471, 473, 706
—— —— in electro-plating, 122
—— —— in rotor bars, 593
——, Effects of, 6, 242
—— flowing in magnetic field, 416, 632
—— generators, 124
—— in a motor, 578, 635
—— in rotor circuit, 572, 574, 576
—— in stator circuit, 573, 576, 578
——, light load, in induction motors, 596, 603
—— measurement, 721
——, Wattless, 369
Curves, candle-power of arc lamps, etc., 701
——, carrying capacity of conductors, 706
——, Characteristic, 459 *et sqq.*, 640, 690
—— for calculation of dispersion coefficient, 580, 581
—— for induction motor design, 587
——, magnetic, 173, 175, *et sqq.*
—— of accumulator voltage, 78, 79
—— —— —— capacity, 69
—— of alternating quantities, 358 *et sqq.*
—— of core losses, 453, 596
—— of current rise, 198, 351
—— of E.M.F. in alternator, 522
—— of electrolytic resistance, 18
——, of glow-lamps, 686, 687
—— of hysteresis, 201, 204, 294
—— of iron losses, 415, 453, 470
Curves of losses in turbo-alternator, 551
—— of magnetisation of iron, 187, 190, 354, 420
—— —— —— of nickel, 189
—— of output coefficients, 465, 589
—— of permeability, 197
—— of pull of magnet, 211
—— —— —— of solenoid, 207, 294
—— of polyphase quantities, 395, 399
—— of temperature rise, 455, 468
——, performance, of induction motors, 600
——, —— of single-phase motor, 618
——, —— of turbo alternator, 551
——, saturation of alternator, 667
——, speed-torque of induction motor, 607
Cyanide solution for use in electro-plating, 115–118
Cyclic irregularity of prime movers, 530

D

Damping coils, 530
Daniell cell, 239, 246
Davy arc lamp, 692
Day load for supply station, 722
Definition of ampere, 239
—— of calorie, 242
—— of coulomb, 240
—— of dyne, 237
—— of erg, 242
—— of farad, 240
—— of gauss, 240
—— of henry, 240
—— of joule, 240, 243
—— of maxwell, 240
—— of ohm, 240
—— of volt, 239
—— of watt, 240
De Laval steam turbines, 477
Demagnetisation, 449
—— in alternators, 676
Demand, effect on cost of supply, 722
—— indicators, 723
Design of continuous current machinery, 427
—— of induction motor, 586
—— testing, 642
Detector, Linesman's, 244
Dielectric strength, 423
Dielectrics, 4
Differential compound motors, 488
—— galvanometers, 248
—— gear of clock meter, 729
Dips, various, in electro-plating, 115–118
Discs of rotor, 583
Dispersion, Magnetic, 579
Dissociation, 38
Distributing boards, 711
Distribution, 762
——, Alternating current, 767, 772
—— by transformers, 768
——, Five-wire, 766, 819
——, Multi-voltage, 767
——, Polyphase, 769
——, Series, 690 764
——, Three-wire, 765, 819
——, Two-wire, 764
——, Voltages of, 765
Dolter surface contact system, 812
Drill for *Drysdale's* permeameter, 656
Drop of voltage in three-wire circuit, 766
Drum armatures, 436
Drysdale's permeameter, 656
Ducts for ventilation, 454, 468
Duplex winding, 440
Dynamometer, 267
Dynamos, Arc, 690
——, Electrolytic, 479
——, Homopolar, 482
——, Section on, 416
——, Turbo, 477
Dyne, Definition of, 237

E

Ears for trolley wires, 803
Earthing strip, 813
Ebonite, 423
Eddy current brakes, 666, 724
—— —— in mercury thermometer, 674
—— —— in rotors, 572
—— —— losses in armatures, 453, 470, 637, 647
Efficiency of accumulators, 76
—— of alternators, 552, 662, 663
—— of homopolar turbo-generator, 486
—— of motors, 637
—— test, 660, 662
Electricity, Theories of, 1, 2
Electrodes, 6, 15
Electrolyte, Diffusion of, 68
Electrolytes, 6, 15
——, List of, 4
Electrolytic bath, 6
—— dissociation, 17
—— dynamos, 479
—— meters, 730
Electromagnet of *G.B.* system, 814
—— of *Lorain* system, 811
—— of motor brake, 501
Electrometer, 28, 258
Electromotive force (E.M.F.), 5, 6
Electron, 3
Electro-plating, 99
Electrotyping, Moulds for, 138, 146
——, Preparation of surface, 140
——, Single-cell, 125, 138
Electrostatic instruments, 279
Elements, Electro-chemical constants, 134
——, Negative and positive, 37
Elihu Thomson's retarding disc, 512
E.M.F., Back, in a motor, 634, 636
——, commutation, 445
——, Explanation of, 5, 6
——, Generation of, 416, 441
—— in rotor, 574
—— of alternators, 417, 524
—— of polarisation, 731
Energy, 3, 8
—— loss in electrolytic meters, 731
——, Transformation of, 636
Equivalent conductivity, 17
Erg, Definition of, 242
Evershed meter, 725, 726
Ewing's hysteresis meter, 657
"Excello" arc lamp, 696
Excitation, 471, 494, 518
—— of interpoles, 496
——, Table showing calculation of, 473
Exciter, Compounding by mea of, 680
Expansion, Coefficient of, 15
External characteristic, 459
Eye, Effect of colours on, 70

F

Farad, Definition of, 240
Faraday disc, 419
Feeder, 763
—— pillars, 779
Ferranti meter, 727
Ferraris on induction motor 511
Field, M. B., method of testing motors, 671
——, —— on single-pha motors, 642
Field excitation, 458, 471, 51 535
—— magnets, 537
—— of alternators, 509
—— of homopolar dynam 483
—— of induction motor, 57
—— of *Thomson* meter, 725
—— resistance, 645
—— winding, 472, 494
Filament, Manufacture of, 684, 688
Fire, Precautions against risk of, 718
Five-wire system, 766
—— —— in railway working, 819
Flame arc lamps, 695
"Flappers" of magnetic brak 502
Flashing voltage, 660
Flexible wires, 705
Flux in air gap, 420, 441
—— in armature, 471
—— in induction motor, 581, 594
—— in inductor alternator, 517
—— in pole, 471
—— in teeth of cores, 45 472
Foot-pound, 8
Force, Field of electric, 15
—— on a conductor, 633
Former-wound coils, 523, 535
Foster arc lamp, 693
Foucault currents, 724
Frequencies, High, 843
—— in use, 771
—— of oscillations, 843
Frequency, Change of, 620
—— in rotor circuit, 573
—— meter, 300
—— of alternators, 508, 524
Friction, 5
——, Electrification by, 1
—— loss in alternators, 596, 6
—— —— in eddy curr brakes, 669
—— —— in supply meters, 725
—— —— of collector brush 456, 485
Fringe of flux for commutation, 445
"Frogs," 805
Fuses, Position of, 710, 712

G

Galvanometers, 244
——, Astatic, 246
——, *Ayrton-Mather* form, 254
——, Ballistic, 251

Galvanometers, *Campbell*, 257
——, *Crompton*, 255–6
——, *D'Arsonval*, 253
——, Differential, 248
——, Reflecting, 249
—— ——, Post Office type, 246
——, Tangent, 244
——, *Thomson* four-coil, 250
Gauss method of determining H, 658
Gauss, Definition of, 240
"*G.B.*" surface contact system, 813
Gearing of tramway motors, 671
Generation, Chemical, 35
Generator, Analysis of, 469
Generators, Current, 124
——, Testing of, 662
Gilding, 122
Glass, 423, 425
Glycerine in indicator, 723
Gramme equivalent, 16
Graphical treatment of alternating-current circuits, 367, 372, 377, 379, 388, 390
Grinding of cast-iron surfaces, 110
Grouping of windings, 525
Guard wires, 805
Gutta percha, 423

H

Hangers for trolley wires, 803
Harcourt standard, 702
Heat, Dissipation of, 456, 481, 498, 596, 667
—— test of transformers, 674
—— value of anode, 36
Heating of alternators, 528
—— of commutator, 456
—— of continuous-current dynamo, 452
—— —— —— generators, 452
—— of field, 457
—— of induction motors, 596, 598
Hefner standard, 702
Hemitropic winding, 522
Henry, Definition of, 240
Heyland compound alternator, 679
—— diagram, 574, 597
—— single-phase motor, 612
Hobart on calculation of dispersion coefficient, 579
—— on commutation, 444, 446, 447
Homopolar dynamos, 482
Hopkinson's method of testing iron, 653
—— method of testing motors, 660
Horizontal component of earth's field, 658
Horse-power of induction motor, 578
Hunting of alternators, 529
—— of synchronous motor generators, 621
Hydraulic commutator press, 433
Hydrometer scales, Table of comparison of, 133
Hysteresis, 201
——, Curves for, 204, 415
——, Energy of, 202
—— in alternators, 663
—— in transformers, 410
—— losses, 453, 470
—— —— in motors, 637, 647
—— meter, 657

I

Idle-current ammeter, 299
Impedance, 370
Indicator maximum demand, 722
Inductance, 371, 377
Induction of currents in a conductor, 416
—— of currents in alternator, 518
—— motor, 511, 570
—— ——, Examples of, 598
—— —— generators, 625, 629
—— —— ——, Construction of, 581
—— —— —— design, 586
—— —— starters, 714
—— —— supply meter, 727
—— regulator, 564
Inductor type alternators, 516
Inspection chambers for conduit, 809
—— cover of motors, 506
Instruments, Classification of, 259
——, Electrostatic, 280
——, Errors in, 263, 266
——, Hot-wire, 273, 275, 277, 279
——, Moving coil, 264
——, —— iron, 260, 262
Insulation, General, 422
—— of accumulators, 76
—— of slots, 439, 524, 536
—— of small cables, 422, 705
—— resistance, 423
—— test of transformers, 672
Insulators, 19
—— for conductor rails, 807
—— for overhead line, 782, 826
—— for trolley wires, 803, 804
——, Leading in, 785
——, List of, 20
——, Table of, 426
Internal characteristic, 459
Interpoles, 468, 639
Ions, 3, 16, 38
Iridium, 732
Iron losses, 453, 470, 552, 578, 595, 618, 671
—— —— in alternators, 526
—— —— in transformers, 410, 415
——, Testing of, *Bidwell's* method, 654
——, —— ——, *Drysdale's* method, 656
——, —— ——, *Hopkinson's* method, 653
——, —— ——, Magnetometer, 656
——, ——, ——, *Rowland's* method, 651
——, —— ——, *S. P. Thompson's* method, 655

J

Jandus arc lamp, 700
Joints in cables, 706
—— in filaments, 685
—— in transformer core, 556
Joule, Definition of, 9, 240, 243
"Juno" arc lamp, 696

K

Kapp and *Housman* separation of losses, 647
—— coefficient, 520
—— method of testing motors, 660
Kapp, Prof., 638
Kathode, 6, 15
Key, Cable testing, 304
——, Condenser, 306
——, *Morse*, 305, 831
——, Multiway, 303
——, Plug, 302
——, *Rymer Jones*, 304
——, Simple, 302
Kilowatt, 9
Kinetic energy of rotor of machine, 648
Kingdon alternator, 516

L

Lag in induction motor, 574
—— of current in single-phase motor, 642
Laminations, Insulation of, 407, 430, 588
Lampholders, 712
Lamp, Arc dynamos, 690
——, ——, Enclosed, 689
——, ——, Examples of, 691–700
——, ——, mechanisms, 690
——, —— Principles of, 689
——, Candle-power and voltage, 687
——, Effect of on supply, 684
——, Efficiency and life of, 686
——, glow, Exhaustion of, 685
——, Manufacture of carbon filament, 684
——, Metallic filament, 687
——, Mounting of filament, 685
Lap windings, 437
Lead of brushes, 451
Lead-covered wires, 710
Leakage coefficient, 471
—— flux of induction motor, 575
—— in dynamos, 421
Leblanc compound exciter, 680
Lifting magnets, 209, 213, 219
Light, Cost of, 721
—— in relation to voltage, 721
Lightning arresters, 758
—— ——, Horn, 760
—— ——, Objects of, 759
—— ——, *Shaw*, 760
—— ——, *Thomson*, 759
—— ——, Water-jet, 760
—— ——, *Wurtz*, 759
Lime bobs, 118
Limits of alternator design, 528
Line, catenary construction, 822
——, Overhead, 782, 823, 826
Linesman's detector, 244
Load on supply station, 92, 722
Local action, 39
Lodestone, 166
Logarithmic decrement, 253, 313
L.C.C. alternators at Greenwich, 541
Lorain surface contact system, 811
Losses, Copper, 453, 498
—— in alternators, 526, 551, 552, 663
—— in continuous-current generators, 470, 485
—— in induction motors, 576, 577, 595
—— in motors, 618, 637
——, Separation of, 646
Lummer-Brodhun photometer, 703

M

Magazine arc lamp, 699
Magnet compound, 167
——, Lifting, 209, 213, 219
——, Natural, 166
—— of eddy current brakes, 667
—— of *G.B.* system, 814
—— of winding gear, 730
——, Poles of, 169
——, Steel, 167
—— winding, 209, 214, 215
Magnetic axis, 169
—— brake on motor, 500
—— circuit, 181, 419, 472
—— density, 420
—— field, Energy of, 200
—— —— of earth, 658
—— flux, 177, 180, 193
—— force of a current, 171, 176
—— induction, Diagram of, 186
—— ——, rules for direction, 183
—— leakage, 419, 474, 569
—— lines of force, 182
—— moment, 169
—— path, 472
—— —— in homopolar dynamo, 483
—— pole, 169, 170
—— —— unit, 237
—— properties of iron, Testing of, 651
—— reluctance, 194
—— separator, 224
—— table, 594
Magnetisation curves, 187, 189, 190, 191, 426, 469, 662
Magnetising current of induction motor, 590, 594
Magnetism, Terrestrial, 170
——, Electro, 170
Magneto-generator for telephone, 881
Magnetometer method of testing iron, 656
Manilla paper, 423
Marble, 423, 425
Maximum demand indicator, 722
Maxwell, Definition of, 240
Measurement of capacity, 334
—— of current, 333, 342
—— of electrolytic resistance, 326
—— of E.M.F., 327, 343
—— of resistance, 315, 345
—— —— —— by differential galvanometer, 324
—— —— —— by ohmmeter, 316
—— —— —— by Wheatstone's bridge, 319
—— —— —— by wire bridge, 325
—— of self-induction, 336
—— of wave form, 338
Measuring instruments, 259
—— ——, Electrostatic, 279
—— ——, Hot wire, 273
—— ——, Moving coil, 264–273
—— ——, —— iron, 259–264
Mercury bath of supply meter, 727
—— in electrolytic meter, 731
Mesh connection of alternators, 401, 525
Metallisation of gutta-percha, 161
—— of wax, 164
Metals, Electro-deposition of, 97
Meters, Chapter on, 721
Methods of Metering, 721
Metric system (C.G.S.), 237
Mica, 423, 424, 433

Microhm, 13
Microphone, 876
Mops for polishing, 118
Mordey method of alternator testing, 663
Mordey-Fricker meter, 730
Morse code, 829
—— key, 305, 831
Motor converters, 629
—— generators, 620–621, 820
—— ——, Synchronous, 511, 621
—— ——, Induction, 511, 625, 626
—— meters, 724
—— starters, 713–717
Motors, Alternating current, 511
——, Characteristics of, 639, 640, 662
——, Classification of, 639
——, Continuous-current, 487
——, Distribution of power in, 636
——, Enclosed, 498
——, General, 416, 510
——, Induction, 511, 570
——, Performance of continuous-current, 458, 495
——, Risk of fire from, 718
——, Variable speed, 492
Moulding in gelatine, 147
—— in gutta-percha, 153
—— in plaster, 148
——, Mounting for, 154
Moulds, Finishing surface of, 163
——, Slinging, 164
Multi-voltage speed control, 767

N

Nernst lamp, 688
Neutral metal, 120
Nickel plating, 115
—— ——, Zinc, wrought work, etc., 119
No-load test of transformers, 673
Non-conductors, 4
Non-inductive winding, 198

O

Ohm, 13
——, "Legal," 23
—— units, 239, 240
Ohm's law, 21
Oil-cooled transformer, 557, 564
Ondographe, 339
"Oriflamme" flame arc-lamp, 697
Oscillations, Electric, 839
——, Explanation of, 841
——, Frequencies of, 843
——, Necessary conditions for, 842
——, Production of, 839
Oscillograph, 340
Osmium lamp, 688
Osmotic pressure, 38
Oudin on induction motors, 716
Output coefficient, 464, 490
—— limits of motors, 638
Over-compounded, 464
Over-compounding of alternators, 683
Overhead system of traction, 606–807
Overhung type of alternator, 544
Overload capacity of induction motor, 586

P

Pacinotti, 638
Paper insulation, 425
Parallel arc, in, 12
—— running of alternators, 528
Parshall on commutation, 444, 446
Pendulum, Ballistic, 252
Performance curves, 501
—— of single-phase motor, 618
Permeability, 196, 419, 420, 429
Perry, *Prof. J.*, on meters, 721
Phase meters (*see* Power factor indicator)
—— displacement in single-phase motors, 610
—— —— in alternators, 521
—— relations in alternating-current meter, 728
—— splitting, 608
Phosphor bronze bearings, 470
Photometers, 702
Photometry, 700
Pivots of meters, 727
Plaster, Hints for using, 151, 152
Plating nickel, 119
—— shop, Equipment of, 124
—— ——, Generators for, 124
—— silver, 115
Plough carrier, 809
—— conduit, 801, 809
Plug key, 302
—— travelling, 304
Points for overhead trolley wires, 805
Polarisation, 38, 40
Pole changing of induction motors, 608
—— construction, 468
——, Laminated, 429
—— of turbo alternators, 549
—— pitch, 430
——, Positive and negative, 37
Poles for commutation, 447, 467, 479, 493, 615
—— of a magnet, 169
Polyphase alternators, 509
Porcelain, 423, 425
Potash for use in electroplating, 115
Potential, 27
—— difference, 28, 30
——, Fall of, 28, 30
Potentiometer, 31, 342
—— for measuring armature resistance, 644
Power, 8
——, Distribution of, in a motor, 636
——, Measurement of, 287, 723
—— factor, 366
—— —— indicator, 297
—— —— of alternator, 526
—— —— of induction motor, 585
—— —— of series motor, 617, 619
Prepayment meters, 733
Presspahn, 423, 424
Pressure as factor of work, 721
—— of alternators, 527, 675
——, Osmotic, 38
—— solution, 38
Prony brake, 664
Pull of magnet, 210
—— of solenoid, 207
Pumice powder for use in electroplating, 115
Purkinje phenomenon, 703

Q

Quantity, Electric, Definition of, 240
—— meters, 722
Quicking, 115

R

Radial type of homopolar dynamo, 485
Rail bonds, 798
Rails, Conductor, 807
—— for tramways, 798
Railway, *City and South London*, 819
—— collecting devices, 825, 828
——, Main line, 821
—— motor characteristic, 821
—— motors, Testing of, 670
——, Overhead construction, 822
——, Single-phase, 825
——, Three-phase, 825
Railways, Electric, 815
——, ——, compared with steam, 815
——, —— motors, Construction of, 828
——, —— ——, Dead weight of, 816
——, —— ——, Power of, 815
——, ——, Multiple unit, 818
——, ——, protection of conductor, 817
——, ——, Track, 817
——, ——, Voltage of, 816, 822
Ranges of winding, 522
Rate of cutting, E.M.F. proportional to, 232, 349, 359
Rateau steam turbines, 478
Rating of motors, 499
Rayner tests on heating of coils, 649
Reactance, 376
Reflecting galvanometers, 249
Registration in electrolytic meters, 730
Regulation test of transformers, 674
—— by induction regulator, 565
—— of alternators, 675
Regulations of authorities as to wiring, 719
Resistance, 6, 12
—— box, 303
——, Carbon frame, 47
—— for temperature measurement, 650
——, Graphical calculation of, 25
—— in parallel, 23
—— in series, 23
——, "Internal," 29
—— leads in single-phase motor, 616
—— measurement (*see* Measurement)
——, —— of armature, 643
—— of brushes, 645
—— of cells, 41
—— of electrolyte, 44
—— of electrolytic meter, 731
—— of field, 645
——, Reciprocal of, 17
——, Temperature coefficient of, 14
Resistances for plating vats, 126–128
Resistivity, 13, 18
—— of alloys, 15
—— of metals, Values for, 14
Resonance, 382
Reversing of motors, 608, 717
Rieter's eddy-current brake, 667
Ring armature, 435, 442
Rise of current in inductive circuit, 198, 351, 354
R.M.S. value in testing insulators, 426
Rocker for collector brushes, 474
Rowland's method of testing iron, 651
Rope brakes, 665
Rotary converters, 621–625, 628
—— ——, Sequence of current changes in, 623
Rotating field of single-phase motor, 514, 640
Rotor, Construction of, 583
—— core, 594
—— of induction motor, 513, 572
—— winding, 584, 608
Rubber, 423, 425

S

Saturation curve, 469, 494, 505
—— —— of alternator, 677
—— of armature teeth, 452
Scouring trough, 115
Scratch brushing, 116, 117
Section insulators, 803
Self-induction, 349
——, Coefficient of, 199, 352
—— in single-phase motor, 641
Separation of losses, 646
Separator, Magnetic, 224
Series, Characteristic, 459
——, connection, 24, 40
—— coils of meter, 727
—— ——, Position of, 474
—— machines, 427, 459
—— motor starters, 714
—— motors, Rating of, 669
—— ——, Single-phase, 507, 616
—— parallel control, 791
—— windings, 440, 497, 502, 727
Sheffield lime for use in electroplating, 117, 118
Shock, Precautions against, 719
Shoes on conduit plough, 809
Short circuit, test of transformers, 673
Shunt, Characteristic, 462
—— machines, 427
—— motor starters, 713
—— of supply meter, 727, 731
—— regulation, 486
—— windings, 472, 727
Silk, 423, 425
Silver plating on copper, 115
—— —— on zinc, pewter, etc. 117
—— —— on iron and steel 118
Sine wave, 355, 373, 418
Single-phase alternators, 509
—— motors, 514, 608–619
—— ——, Theory of, 640
Siphon recorder, 838, 866
Simmance-Abady photometer, 703
Size of induction motor, 586
Skate, 812, 813
Skin effect, 843
Slate, 423, 425
Slip of induction motor, 512, 573, 578, 607
Slip-ring connections, 601
Slip-rings, 599
Slots in armatures, 430, 453
—— of alternator, 523, 536
—— of induction motor, 582, 583, 588, 593
Solenoid, Field of, 206
——, Pull of, 207
Solution, Barium sulphide, 121
—— for brassing, 102
—— for copper, 103
—— for nickel, 104
—— for gilding, 104
—— for silver-plating, 100, 115

Solution for stripping, 106
——, Gun-cotton, 121
—— pressure, 38
Solutions, Management and estimation of, 121
Space factor of windings, 524, 535
Spacing of conductors, 519
Sparking, 443, 617, 659
—— limit, 638
Special work, Cost of, 809
Speed control, 766, 767
—— counters, 645
—— effect on cooling, 455
—— —— on efficiency, 639
——, Factors of, 634
——, Measurement of, 645
—— of alternators, 509
—— regulation of induction motors, 513, 606
—— —— of motors, 497, 717, 718
Spider of continuous-current motor, 494
—— —— —— generator, 469
—— of induction motor, 605
Split-phase motors, 515, 609
Squirrel-cage rotor, 514, 583, 585
Standard cells, 59, 61, 241
—— ——, Table of, 242
—— of current strength, 240
—— of E.M.F., 59, 241
—— of resistance, 241
—— sizes of stampings, 587
Standards of light, 701
Star connection, 401, 771
—— —— of alternators, 525
Starting coil, 609, 612
—— —— induction motors, 585, 603
—— —— of rotary converters, 624
—— —— of single-phase motors, 642
Stator, Construction of, 581
—— core, 594
—— of induction motor, 513, 573
—— windings, 514, 582
Steel castings, 428
—— conduit, 708, 709
—— ——, Fittings for, 709
Stream lines of electrolytic meter, 733
Stud of *Doller* system, 812
—— of *Lorain* system, 811
Sumpner, *Dr.*, method of testing machines, 648
—— —— on transformer testing, 674
Surface-contact system, 801, 811
——, cooling of armatures, 456
Suspension of overhead wires, 802
—— of anodes, 123
Switchboard, Cellular, 741, 742, 743
——, Exciting, 741, 745
——, Extra high-tension, 745
——, *Ferranti*, 739, 742, 745
——, Flat-back, 741
——, General requirements of, 739
——, High-tension, 741, 742, 744, 747
——, Low-tension, 741
——, Types of, 739
Switch piece of *G.B.* system, 813
Switch-ring contact, 129
Switches, Arcing of, 735, 736
——, carbon contacts, 735
——, circuit breakers, 753, 754
——, classification, 734
——, Current density in, 735
——, Design of, 734
—— for lighting circuits, 712
Switches, high-tension oil, 738, 757
——, Hot contacts, 736
——, Insulation of, 736
——, Knife, 738
——, length of air brake, 736
——, Relay operated, 755
——, Remote control, 739, 744, 746, 756
——, Reversing, for motors, 717
——, typical constructions, 738
Synchroniser, 301, 757
—— rotary, 758
Syntony, 856

T

Table of copper wire, 422
—— of electro-chemical constants, 134
—— of hydrometer scales, 133
—— of insulators, 426
—— of resistances, 20
—— of specific gravities (acids), 136
—— of standard cells, 242
—— of thermometer scales, 137
—— of wireless telegraphy detectors, 861
Tachometers, 645, 646
Tandem control of induction motors, 608
Tangent galvanometer, 246
Tantalum lamp, 688
Teeth of armatures, 420, 452
Telegraph, 829
——, A.B.C., 832
—— circuits, 834
—— code, 829
——, Diplex working, 837
——, Double-current working, 835
——, Duplex working, 836
——, Morse inker, 831
——, ——, Key for, 305, 831
——, Mulitplex working, 838
——, Quadruplex working, 837
—— relays, 833
—— repeater, 833
——, Single-needle, 829
——, Siphon recorder, 838, 866
—— sounder, 831
—— translator, 833
——, Wireless working 851 (*see also* Wireless Telegraphy)
Telephone, 875
—— arresters, 883, 900
—— circuits, 886, 890, 893, 894, 901, 902, 907
——, —— for central battery working, 898, 901, 902
——, ——, for engaged test, 892, 894, 908
——, —— for exchange cables, 897
——, —— for lamp call, 909
——. —— for multiple, 893, 895
——, —— for operator's cord, 894
—— ——, for plugs, 888
——, —— for P.O. system, 907
——, —— for switchboard, 890
——, exchange switchboards, 887, 889, 891, 904, 905, 908
——, Fuse for, 904
——, Heat coils, 884, 900
—— indicators, 887, 893, 906, 909
—— jacks, 887, 893, 896, 906
—— keys, 889, 890, 894, 905
—— line construction, 910
—— magneto cut-out, 881
—— magneto-ringer, 881
—— meters, 904
Telephone, overhouse construction, 913
—— plugs, 888, 893, 896, 906
——, Polarised bell for, 882
—— receivers, 879
—— relays, 898, 901, 907
—— switch-hook, 882
—— transmitters, 876
Temperature coefficient, 14, 15
—— effect on brake disc, 724
—— —— on insulation, 424
—— —— on resistance, 731
—— in motors, 499
—— of homopolar dynamo, 487
—— of induction motors, 596, 598
—— rise in armature, 455
—— —— in field coils, 457, 468, 473
—— testing, 468, 648, 660, 670
Test curves from *Heyland* diagram, 596
Testing design, 642
—— motors, 560, 664, 671
—— of alternators, 662
—— of iron, 651
—— of lighting installations, 720
—— speed, 645
—— temperature, 648, 660, 670
—— transformers, 672
—— workshop, Chapter on, 659
Thermit welding, 800
Thompson's S.P. Permeameter, 655
—— —— alternator patent, 516
Thomson bridge, 644
——, *Elihu*, supply meter, 724
—— four-coil galvanometer, 250
Three-phase connections, 401, 771
—— distribution, 769
—— measurement of power, 402
—— relations, 399
Three-wire system, 765
—— —— in railway working, 819
—— —— with homopolar machine, 485
Thury system of transmission, 786
Time constant, 351
Tirrel voltage regulator, 681
Torque and speed curves, 640
—— constant in meter, 729
——, Factors of, 632
—— of induction motor, 577, 603
Traction, comparison of systems, 821
——, horse-power required, 788
——, Methods of, 787
—— motors, 499, 506 (*see also* Tramways and Railways)
Tramways, Electric, 787
——, —— brakes, 793
——, —— car circuit, 793, 801
——, —— —— controller, 792
——, —— —— trucks, 795
——, —— —— wheels, 797
——, —— life guards, 798
——, —— motor characteristics, 791
——, —— —— rating, 790
——, —— —— suspension, 790
——, —— power brakes, 794
——, —— —— required, 788
——, —— rail welding, 799
——, ——, Series parallel control, 791
——, —— track brakes, 794
Tramways, Electric, track construction, 798
Transformer action in single-phase motors, 617
Transformers, 554–569
——, Constant-current, 568
——, Continuous-current, 620
——, diagrams, 405, 409, 413
——, Eddy currents in, 407, 410
—— for oscillations, 844
——, Hysteresis in, 410, 411
——, Iron losses in, 410, 415
—— leakage, 404, 413
——, Manufacture of, 556, 559
——, Placing of, 772
——, Testing of, 672
——, Types of, 404
——, Welding, 566
Transmission, 510
——, *Carquinez Straits*, 784
——, Conditions of, 763
——, Difficulties of, 762
——, Insulators for, 782, 785
—— line, 781
——, Reasons for, 763, 780
—— series, 786
——, Systems of, 762, 780
——, Voltage of, 763, 781, 783
Trolley arm, 806
—— head, 806
—— mast, 806
—— wheels, centre and side running, 802
—— wires, 805
Turbo-alternators, 548
—— construction, 551
Turbo-dynamos, 477
Two-phase relations, 395, 398, 769
—— winding, 394, 521

U

Unbalancing of alternators, 663
Unit, B.A. of resistance, 23
——, B.O.T., 722
——, Current, 238
——, E.M.F., 238
—— field, 238
—— force, 237
——, Magnetic pole, 237
—— of heat, 242
—— of length, mass, and time, 236
—— of resistance, 239
—— of work, 242
——, *Siemens*' resistance, 23
Units, "Absolute" or "C.G.S.," 239
——, Practical, 239

V

Variable-speed motor, 492
Varnish, methyl-acetate, 121
Vats, plating, 115–117
Vector diagram of three-phase motor, 571
Ventilation of cores, 432, 454, 470, 475, 537, 542
—— of motors, 468, 469, 603, 606
Vertical component of earth's field, 652
—— ——, Testing of, 658
Violle standard, 701
Volt, 9, 23
——, Definition of, 239, 240
Voltaic Cell, 2, 36
—— circuit, 4

Voltage drop, 30
—— —— in homopolar dynamos, 486
—— —— in supply meters, 727, 733
—— effect on light, 721
—— limit of alternators, 509, 524
—— —— of direct-current motors, 507
—— reactance, 446
—— regulation of alternators, 527, 675–683
—— variation, 721
Voltameter, 309, 333
Voltmeter, Electrostatic 279,
—— error, 293
——, Hot wire, 273
——, Induction type, 295
——, Moving coil, 264
——, —— iron, 259
Voltmeters, 273
——, *Ayrton* and *Perry* instrument, 274
——, *Cardew* instrument, 274
Vulcanite, 423

W

Water-cooled transformers, 564, 568
Watt, Definition of, 240
—— loss per square inch, 596
Watt, Value of, 9
Wattless current, 369
Wattmeters, 267, 723
——, Deflection, 271
——, Error in, 294, 392
—— for alternating currents, 269
——, *Kelvin*, 272
——, *Sumpner*, 296
——, *Swinburne's*, 268
——, *Duddell-Mather*, 269
Wave windings, 437, 442
Waves, Electric, 846
——, ——, Laws of, 849
——, ——, Oscillators for, 847, 849
—— of E.M.F., 417
Wedges in turbo-generators, 479, 551
Welding transformers, 566
Wheatstone's bridge, 319
Windage in eddy current brakes, 596, 669
Winding gear of clock meter, 730
—— of alternator, 518
—— of armatures, 435, 440, 485, 512
—— of stator, 582
——, Single-coil and double-coil, 521
——, Three-phase, 521
Windings, continuous-current, 435
—— ——, Advantages of, 442–443
Wireless telegraphy, 851
—— ——, Action of aerial in, 853
—— ——, Aerials for, 852, 854, 863
—— —— coherers, 851, 860, 865, 871
—— —— ——, Self-restoring, 862
—— ——, Connections to aerial, 853, 855, 859
—— ——, Currents and potentials in aerials for, 858
—— —— damping, 858
—— ——, *De Forest* apparatus, 872
—— —— detectors, 859, 861
—— —— ——, *Marconi's* magnetic, 872
—— ——, Effect of weather on, 863
—— ——, Electrolytic, 873
—— ——, *Fessenden* apparatus 873
—— ——, *Lodge - Muirhead* system, 863
—— ——, *Marconi* apparatus, 870
—— ——, Syntony in, 856
—— ——, Thermal, 873, 874
—— ——, tuning, 869
Wires, Flexible composition of, 422, 705
—— for interior wiring, 705
—— for machine winding, 422
——, Guard, 805
Wires, Insulation of, 421, 705
——, limits of sizes used, 422, 705
——, Size of, for winding, 593
——, Trolley, 805
Wiring, 705-712, 718
——, Arrangement of, 710
——, Systems of, 708
Wood-casing, 708
Work, 5, 6, 8, 242
——, Measurement of, 721
——, Two factors of, 8
Wright, A., on charging for supply, 722

Y

Yoke for conduit construction, 807
—— for field system of dynamo, 469

Z

Zero deflection wattmeters, 269
Zig-zag dispersion, 579
Zinc amalgamating, 125
——, heat value, 36, 37
——, Consumption of, 38
Zincs, Amalgamated, 40

BUSINESS FIRMS REFERRED TO

Adams Manufacturing Co., 713
Bastian Meter Co., 731, 733
Beardmore and Co., 475
British Electric Transformer Co., 558
British Insulated and Helsby Cables, Ltd., 567
British Thomson-Houston Co., 443
British Westinghouse Electric and Manufacturing Co., 481, 530, 615, 678
Brown, Boveri, and Co., 429, 431, 434, 436, 537, 543, 549, 563, 564, 604
Bruce, Peebles and Co., 430, 530, 536, 598
Chloride Accumulator Co., 93
Crocker-Wheeler Co., 430
Crompton and Co., 479
Dick, Kerr and Co., 454, 500, 505, 537, 549
D.P. Battery Co., 73, 74, 83, 91
Electric Construction Co., Ltd., 474, 537
E.P.S. Co., 83
Ferranti, Ltd., 299, 739, 742, 745
Fraser and Chalmers, 478
Ganz and Co., 771
Geipel and Lange, 277
General Electric Co., 679
Greenwood and Batley, 477, 604
Johnson and Phillips, 275, 488, 490, 542, 554, 586, 613
Lancashire Dynamo and Motor Co., 474, 490, 532, 601
Langdon-Davies Motor Co., 609
Laurence Scott and Co., 469, 492, 501
Le Carbone, 456
Machinen Fabrik Oerlikon, 517
Morris and Lister, Ltd., 668
Oliver and Co., 691
Thomas Parker, Ltd., 499
C. A. Parsons and Co., 549
Phœnix Dynamo Co., 467
Rhodes Manufacturing Co., 490
Siemens Bros., 478
Siemens Bros. Dynamo Works, Ltd., 532, 603
J. H. Tucker and Co., 712
Tudor Accumulator Co., 85
Western Electric Co., 889, 893
Vickers, Sons, and Maxim, 465, 475, 499, 531

PRINTED BY CASSELL AND COMPANY, LIMITED, LA BELLE SAUVAGE, LONDON, E.C.

UNIVERSITY OF MICHIGAN
3 9015 06717 6829